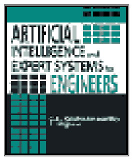

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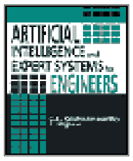

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Preface

The book is aimed at bringing out a comprehensive presentation of Artificial Intelligence (AI) based methodologies and software tools wherein, for the first time, the focus is on addressing a wide spectrum of problems in engineering.

Expert system methodology has been applied in the past to a number of problems of planning, design, diagnostics etc. However, the problems of engineering design have not been adequately addressed, since these problems have to be addressed in an integrated manner with knowledge from different domains and sources. Continued research in the last ten years has recently resulted in the emergence of new methodologies which will enable building of automated integrated design systems that will have the ability to handle the entire design process. These methodologies include design synthesis, design critiquing, case-based reasoning etc., leading to concurrent engineering. Details of these methodologies and tools are at present available only in the form of technical papers and reports of research projects that have been carried out in academic and other institutions.

Many research and development projects have been carried out by the authors in the past few years, and prototype systems have been developed for specific applications to engineering systems. During this process, the authors have proposed generic frameworks and have developed efficient software tools to meet the requirements of engineering design. This intensive work, coupled with the teaching of a graduate course on Computer-Aided Design, motivated the authors to write a book on the subject with descriptions of different methods and a presentation of software tools that meet the requirements of integrated knowledge-based systems in engineering. The authors hope that the book will serve as a textbook for students and teachers, and the software frameworks and tools will provide the requisite resource material to researchers and professionals who are interested in developing knowledge-based systems in various disciplines of engineering.

The book is divided into seven chapters. The first chapter presents an overview of the developments in the areas of AI and Knowledge-Based Expert System (KBES) applications to engineering. The relevance and importance of the use of AI-based methodologies for solving engineering problems are well brought out in this chapter.

The predominant component of any AI-based program is in the extensive use of search techniques. Depending on the nature of the problem being solved and the context, appropriate search techniques are to be adopted. Chapter 2 presents different search techniques used in AI-based programs.

KBES is the most popular and successful of the AI-based tools, that have been evolved to address problems in planning, diagnosis, classification, monitoring and design. Different knowledge representation schemes such as rules, semantic nets and frames are presented in Chapter 3. Inference mechanisms which drive the knowledge base are also presented with the help of simple engineering examples. The architecture of an expert system shell, developed by the authors, called DEKBASE (Development Environment for Knowledge-Based Systems in Engineering) is presented along with the examples illustrating the use of DEKBASE to develop production rule-based expert systems.

Chapter 4 presents the concepts of design synthesis and the techniques used to generate multiple solutions with predefined constraints. The domain decomposition-recomposition technique useful for engineering design is explained with examples. The architecture and framework for design synthesis and computer implementation of a generic tool, GENSYNT (GENeric SYNthesizing Tool), are presented and the use of GENSYNT is explained through examples.

Engineering design process involves use of knowledge sources from different domains. Any feasible solution generated from the consideration of one domain has to be evaluated for satisfaction of the concerns of other domains participating in the process. A methodology for design critiquing and evaluation of a solution is presented in Chapter 3. The architecture of GENCRIT (GENeric CRItiquing Tool) is explained with sample problems.

Another major development in AI-based methodology is the emergence of Case-Based Reasoning (CBR) which aims at generation of solutions based on past cases stored in casebases with the application of appropriate reasoning mechanisms. The requirements of a CBR-based model for engineering design and a generic frame work, CASETOOL (CASE-based reasoning TOOL), are presented in Chapter 6.

Engineering design involves a class of complex generative tasks whose solutions depend on the cooperative participation of multiple specialists. In order to develop a knowledge-based system an analysis of all the tasks involved has to be performed. Based on the task analysis the developer has to identify the AI methodologies needed and propose a process model for the system. The process model should facilitate horizontal and vertical integration of the tasks involved in the entire design process. For a better understanding of the process models needed for developing knowledge-based systems for real-life problems, case studies of typical prototype systems are presented in chapter 7.

It is felt by the authors that an understanding of AI-based methodologies, and the generic framework and tools presented in the book, can be made more effective, if readers get an opportunity to use these tools on computers and acquire hands-on experience. Educational versions of the four software tools are provided in the floppy diskette. The software DEKBASE with a rule base inference engine and a frame management system provides a platform for inclusion of other generic tools, GENSYNT, GENCRIT and CASETOOL. The tools are implemented on PC-based systems under a DOS environment. The use of the software tools is illustrated in the Appendices I to III for the examples described in various chapters of the book.

The authors would like to acknowledge that it was the Indo-US project under the NSF grant INT 8913816 on KBES for Civil Engineering Design, in collaboration with Professor Steven J. Fenves of Carnegie-Mellon University, that had significantly contributed to the development of the software tools, particularly DEKBASE, presented in this book. The authors would like to express their gratitude to Professor Steven J. Fenves for his interaction through the above project which provided the motivation to the authors for the research and development work in this area.

The four software modules presented in this book are due to the dedicated efforts of the Indo-US project team and the authors would like to place on record their deep appreciation and gratitude to the project officers, affectionately referred to as Indo-Americans, M/s. C.S. Rao, S. Suresh and H. Shiva Kumar. The authors thank Mr. Shaikh Karimulla Raja for his contribution to the development of a few modules of DEKBASE and to a number of graduate students for testing DEKBASE. The authors would also like to acknowledge Mr. H. Shiva Kumar and Mr. S. Suresh for their contributions in the development of two prototype systems SETHU and ODESSY which are presented as case studies in this book and for their inputs at various stages of writing this book. The case study dealing with the design of the shape of the body of a car was based on the project work carried out by M/s. Harshawardhan Shetty and Biju Baby under the direction of Dr. N. Ramesh Babu of the Mechanical Engineering Department at IIT, Madras, and the authors would like to thank them for contributing to the development of the system described in Chapter 7.

The authors would like to thank their faculty colleagues Professor V. Kalyanaraman and Professor N.

Rajagopalan for their technical contribution as co-investigators of the Indo-US project. The description in Chapter 7 of GENESIS, a prototype system for plannnig and design of steel industrial structures, and of the architecture of the Integrated Engineering System (IES), is based on the work of Dr. S. Sakthivel under the direction of our colleague Professor V. Kalyanaraman. The authors would like to thank them for making it possible to include them in this book.

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The authors would like to thank the authorities of the Indian Institute of Technology, Madras and particularly acknowledge the CE Departmental Computer Facility where the software development work was carried out.

The fillip to write this book came from Professor W.F. Chen of Purdue University. It was his suggestion that the authors write a book under a series that he has been editing. The authors would like to thank Professor Chen for his encouragement and to Mr. Navin Sullivan and Ms. Felicia Shapiro of CRC Press for their support in the publication of this book.

C. S. Krishnatnoorthy
S. Rajeev

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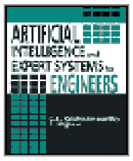

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Chapter 1 Introduction

1.1 General

Engineer utilise principles of science and mathematics to develop certain technologies. These technologies are then used to create engineered artifacts such as products, structures, machines, processes or entire systems.

However, this is too abstract a definition for the engineer's sphere of operation. It must be analysed in greater detail for an understanding of how engineers create the artifacts that improve the quality of life. When an engineer creates an artifact in any area of application, he has to employ a host of related activities like planning, conceptual design, analysis, detailing, drafting, construction, manufacturing and maintenance. Depending on the type of problem that is being addressed and the domain, different combinations and different sequences of these activities are undertaken. Right from the days of ENIAC, the first digital computer, computers have been extensively used by the engineering community to expedite or automate some of the numerous tasks. The history of the use of computers in engineering problems parallels the developments in computer hardware and software technology. Such developments have advanced at such an unbelievable pace in the past fifteen years that today's desktop computers are far more capable than the mainframe computers of the last decade. Developments are not constrained to faster CPUs alone. The emergence of improved paradigms such as parallel and distributed computing, backed up by appropriate software environments, has virtually transformed the direction of research in computer usage in engineering. From the development of faster and faster algorithms, we have moved to developments for evolving improved methods of assistance. This has resulted in the transformation of computers from large numerical computing machines to aids to engineers at every stage of problem solving.

Numerical computing-intensive tasks were the early applications attempted to be solved with the aid of computers in the early days of computer usage by the engineering community. Research in the areas of computer graphics, database management systems and Artificial Intelligence (AI) along with the development of faster and more powerful hardware platforms accelerated and widened the use of computers for engineering problem solving. Computer graphics tools improved the visualisation capabilities, thereby making it possible for complete graphical simulation of many engineering processes. DataBase Management

Systems (DBMS) provided engineers with necessary tools for handling and manipulating the large amount of data generated during processing in a systematic and efficient manner. Integration of spatial information handling and graphical presentation with DBMS provided a very powerful tool, viz., the Geographical Information System (GIS), which has really revolutionised computer-assisted execution of many tasks in many disciplines of engineering. Still, all these developments helped only numerical computing-intensive, data-intensive and visualisation-based problems. One of the major tasks in many of the activities mentioned earlier is decision making, which is required in different stages of execution of each of the tasks. Decision making requires processing of symbolic information in contrast to the conventional data processing, handling of facts and inference using domain knowledge. Inference is nothing but search through the knowledge base using the facts. The intensive research carried out in the area of AI in the last four decades resulted in the emergence of a number of useful techniques which can be used for solving many complex problems.

1.2 Developments in Artificial Intelligence

In the early 1950s Herbert Simon, Allen Newell and Cliff Shaw conducted experiments in writing programs to imitate human thought processes. The experiments resulted in a program called Logic Theorist, which consisted of rules of already proved axioms. When a new logical expression was given to it, it would search through all possible operations to discover a proof of the new expression, using heuristics. This was a major step in the development of AI. The Logic Theorist was capable of quickly solving thirty-eight out of fifty-two problems with proofs that Whitehead and Russel had devised [1]. At the same time, Shanon came out with a paper on the possibility of computers playing chess [2].

Though the works of Simon et al and Shanon demonstrated the concept of intelligent computer programs, the year 1956 is considered to be the start of the topic *Artificial Intelligence*. This is because the first AI conference, organised by John McCarthy, Marvin Minsky, Nathaniel Rochester and Claude Shanon at Dartmouth College in New Hampshire, was in 1956. This conference was the first organised effort in the field of machine intelligence. It was at that conference that John McCarthy, the developer of LISP programming language, proposed the term **Artificial Intelligence**. The Dartmouth conference paved the way for examining the use of computers to process symbols, the need for new languages and the role of computers for theorem proving instead of focusing on hardware that simulated intelligence.

Newell, Shaw and Simon developed a program called General Problem Solver (GPS) in 1959, that could solve many types of problems. It was capable of proving theorems, playing chess and solving complex puzzles. GPS introduced the concept of means-end analysis, involving the matching of present state and goal state. The difference between the two states was used to find out new search directions. GPS also introduced the concept of backtracking and subgoal states that improved the efficiency of problem solving [3]. Backtracking is used when the search drifts away from the goal state from a previous nearer state, to reach that state. The concept of subgoals introduced a goal-driven search through the knowledge. The major criticism of GPS was that it could not learn from previously solved problems. In the same year, John McCarthy developed LISP programming language, which became the most widely used AI programming language [4].

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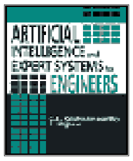

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Kenneth Colby at Stanford University and Joseph Weizenbaum at MIT wrote separate programs in 1960, which simulated human reasoning. Weizenbaum’s program ELIZA used a pattern-matching technique to sustain very realistic two-way conversations [5]. ELIZA had rules associated with keywords like ‘I’, ‘you’, ‘like’ etc., which were executed when one of these words was found. In the same year, Minsky’s group at MIT wrote a program that could perform visual analogies [6]. Two figures that had some relationship with each other were described to the program, which was then asked to find another set of figures from a set that matched a similar relationship.

The other two major contributions to the development of AI were a linguistic problem solver STUDENT [7] and a learning program SHRDLU [8]. The program STUDENT considered every sentence in a problem description to be an equation and processed the sentences in a more intelligent manner. Two significant features of SHRDLU were the ability to make assumptions and the ability to learn from already solved problems.

Parallel to these developments, John Holland at the University of Michigan conducted experiments in the early 1960s to evolve adaptive systems, which combined Darwin’s theory of survival-of-the-fittest and natural genetics to form a powerful search mechanism [9]. These systems with their implicit learning capability gave rise to a new class of problem-solving paradigms called genetic algorithms. Prototype systems of applications involving search, optimisation, synthesis and learning were developed using this technique, which was found to be very promising in many engineering domains [10].

Extensive research and development work has been carried out by many to simulate learning in the human brain using computers. Such works led to the emergence of the Artificial Neural Network (ANN) [11,12] as a paradigm for solving a wide variety of problems in different domains in engineering. Different configurations of ANNs are proposed to solve different classes of problems. The network is first trained with an available set of inputs and outputs. After training, the network can solve different problems of the same class and generate output. The error level of the solution will depend on the nature and number of problem sets used for training the network. The more the number and the wider the variety of data sets used for training, the lesser will be the error level in the solutions generated. In fact, this technique became very popular among the engineering research community, compared to other techniques such as genetic algorithms, due to simplicity in its application and reliability in the results it produced.

All these developments that took place in the field of AI and related topics can be classified into eight specialised branches:

1. *Problem Solving and Planning*: This deals with systematic refinement of goal hierarchy, plan revision mechanisms and a focused search of important goals [13].
2. *Expert Systems*: This deals with knowledge processing and complex decision-making problems [14–16].
3. *Natural Language Processing*: Areas such as automatic text generation, text processing, machine translation, speech synthesis and analysis, grammar and style analysis of text etc. come under this category [17].
4. *Robotics*: This deals with the controlling of robots to manipulate or grasp objects and using information from sensors to guide actions etc. [18].
5. *Computer Vision*: This topic deals with intelligent visualisation, scene analysis, image understanding and processing and motion derivation [6].
6. *Learning*: This topic deals with research and development in different forms of machine learning [19].
7. *Genetic Algorithms*: These are adaptive algorithms which have inherent learning capability. They are used in search, machine learning and optimisation [9–10].
8. *Neural Networks*: This topic deals with simulation of learning in the human brain by combining pattern recognition tasks, deductive reasoning and numerical computations [11].

Out of these eight topics, expert systems provided the much needed capability to automate decision making in engineering problem solving.

1.3 Developments in Expert Systems

Although ANN and Genetic Algorithms (GA) provided many useful techniques for improving the effectiveness and efficiency of problem solving, expert systems and developments in related topics made it possible to address many down-to-earth problems. Expert system technology is the first truly commercial application of the research and development work carried out in the AI field. The first successful expert system DENDRAL, developed by Fiegenbaum, demonstrated a focused problem-solving technique which was not characterised in AI research and development [20]. The program simulated an expert chemist's analysis and decision-making capability. A number of expert systems in different domains, such as geological exploration, medical diagnosis etc., were developed using the concepts presented by Fiegenbaum in DENDRAL. There was apprehension among the AI community to accept expert systems as AI programs, since they used specific knowledge of a domain to solve narrow problems. Development of practical applications using the techniques of expert systems accelerated with the introduction of two new concepts, viz., scripts and frames. Roger Schank in 1972 introduced the concept of 'script' that represents a set of familiar events that can be expected from an often-encountered setting [21]. Minsky in 1975 proposed the concept of 'frame', which helps in a structured representation of scenarios and objects [6]. A combination of heuristics with scripts or frames considerably improved the capability of knowledge representation and inference strategies in expert systems. Many knowledge-based expert systems were developed in engineering and non-engineering domains. Stand-alone expert systems did not appeal much to the engineering community due to their limited applicability to narrow problem domains. Expert systems were found to be ideal for integrating different programs in a domain resulting in the development of decision support systems. Decision support systems integrate heuristic knowledge-based inference, description of scenarios and situations using a network of frames, objects or scripts, conventional programs and databases.

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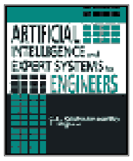

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Parallel to these developments in AI, researchers in different engineering disciplines concentrated on identifying the generic nature of problem-solving tasks and on the application of the AI techniques to solve the tasks in a generic manner. Such an approach gave rise to a number of generic problem-solving models depending on the nature of the knowledge required and the nature of the information being processed [22].

Though expert systems using heuristic models are useful to represent different types of knowledge, they are inadequate to address engineering design problems in an integrated manner. Engineering design generally follows a generate-and-test philosophy, in which solution(s) are generated and then evaluated against acceptability criteria. Generation and evaluation of one solution at a time may not be an effective approach in many situations, where the number of possible solutions that can be generated is combinatorially explosive. Knowledge-based models such as design synthesis, design critiquing, case-based reasoning etc., were proposed to address specific types of problems in engineering design. Detailed descriptions of these generic design methodologies are presented in Chapters 4, 5 and 6, respectively, along with discussions on implementation issues and illustrative examples. Design synthesis deals with knowledge-based generation of multiple solutions. Evaluation of solutions generated and their ranking is done using design critiquing. Case-based reasoning deals with generation of solutions from a casebase generated using past cases.

1.4 Role of AI and Expert Systems in Engineering

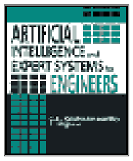
It has already been seen that different tasks in engineering problem solving require different computational tools. Inference or deduction from a set of facts, which simulate intelligent decision making, plays a major role in many problem-solving tasks. For instance, the design stage is a highly creative decision-making activity. Creativity implies the ability to produce novel solutions which are better than previous solutions. The computational tools that assist designers should be such that they should make the designers more creative. Just as creativity is linked to the intelligence and experience that the designer has, the computational tools that assist the designers to be more creative should also have intelligence built into them and they should be able to use expert knowledge of the problem domain for decision making. AI and expert systems technology along with tools such as GAs and ANNs provide techniques for simulating intelligence in decision making, evolution and learning in computers. Like design, activities such as planning and management also can be improved with the use of intelligent tools.

Development of comprehensive software solutions in many engineering disciplines requires a seamless integration of different types of computational tools. Simple techniques of knowledge-based systems technology such as problem decomposition, knowledge organisation in different forms and at different levels and easy control of knowledge processing provide ideal techniques for the smooth integration of different tasks in an application. In addition, adaptation of problem solving to varying environments and requirements can be easily achieved using techniques provided by AI and expert systems.

Any problem-solving process has to be transparent to the engineer. This requires that the model adopted should be simple and the process carried out in the most natural manner. It minimises the number of transformations that the information goes through resulting in retention of clarity and simplicity of implementation. The problem-solving models adopted vary depending on the tasks the problem constitutes, the kind of information used for processing, the method of solving different tasks and the nature of data flow from one task to the other. Also, different models can be applied to the same task; the selection of model being decided by the number of factors characterising the domain. Consider, for instance, a design task. Most design processes in engineering follow the generate-and-test philosophy, in which solutions are generated first, and then evaluated for different functional requirements. Numerical models used in optimisation techniques can be used for generating design solutions.

Different AI-based search techniques can also be employed for generating designs. Some techniques generate just one solution at a time, whereas some other techniques simultaneously generate many feasible solutions. Mathematical optimisation techniques and rule-based expert systems generate just one solution for evaluation. GAs and design synthesis can generate many feasible solutions, resulting in a choice of design solutions for the designers to select from. The case-based reasoning technique uses past solutions stored in a case base to generate a solution for the present requirement. It is the nature of the problem domain and the grainsize of the functional requirements that decides the appropriateness of a model to be used for a task. Similar is the case with evaluation. Depending on the nature of the knowledge, the data and the interaction between them, different models can be used for evaluation or critiquing of a generated design or a plan. Developments that took place in AI and engineering problem solving in the past few years resulted in the emergence of many computational models for different engineering tasks. The book deals in detail concepts, architecture and implementation issues, with real life examples on many such AI-based models.

In the real-world application of computers in engineering, the current trend is to integrate the various tasks of a given problem. Depending on the type of task, the knowledge and processing required may involve use of numerical models, database systems, visualisation tools and decision-making models to provide solutions that need human expertise. Thus to address a wide spectrum of tasks, AI and expert system technologies provide the much-needed software tools to integrate the various processes to build knowledge-based systems for computer aided engineering [23]. To meet these demands of the future, the AI and expert system methodologies are presented in the following chapters of the book. These methodologies and associated tools will be required to provide solutions for various tasks and to build integrated systems for computer aided engineering.



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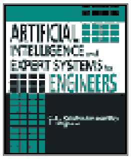

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Chapter 2
Search Techniques

2.1 Introduction

Artificial Intelligence (AI) technology provides techniques for developing computer programs for carrying out a variety of tasks, simulating the intelligent way of problem solving by humans. The problems that humans solve in their day-to-day life are of a wide variety in different domains. Though the domains are different and also the methods, AI technology provides a set of formalisms to represent the problems and also the techniques for solving them. What AI technology provides us is what is described in the above sentences. Based on this, it is very difficult to precisely define the term *artificial intelligence*. Different people working in this topic for many years have proposed different definitions. According to Rich, AI is the study of how to make computers do things at which, at the moment, people are better [1]. It is observed that it is equally difficult to define human intelligence. Some of the essential activities associated with intelligence are listed in reference [1–2] and they are given below.

a) To respond to situations flexibly

b) To make sense out of ambiguous or contradictory messages

c) To recognise the relative importance of different elements of a situation

d) To find similarities between situations despite differences which may separate them

e) To draw distinctions between situations despite similarities which may link them

Simulation of the above activities in a computer is difficult. Also, most of the above actions are used by engineers in carrying out tasks such as planning, design, diagnosis, classification, monitoring etc. Hence, it is essential to look at them more closely in order to understand how they can be formally represented and used.

Newell and Simon [3] proposed the *physical symbol system hypothesis* in 1972, which forms the heart of all the research and development work that takes place in the field of AI. It consists of a definition of a symbol structure and then a statement of the hypothesis, which is given below.

"A physical symbol system consists of a set of entities called symbols, which are physical patterns that can occur as components of another type of entity called an expression (or symbol structure). Thus, a symbol structure is composed of a number of instances or symbols related in some physical manner (such as one instance being next to another). At any instant of time the system will contain a collection of these symbol structures. Besides these structures, the system also contains a collection of processes that operate on expressions, creation, modification, reproduction and destruction. A physical symbol system is a machine that produces through time an evolving collection of symbol structures. Such a system exists in a world of objects wider than just these symbolic expressions themselves."

They then state the hypothesis as:

A physical system has the necessary and sufficient means for general intelligent actions.

The only way this hypothesis can be validated is by experimental and empirical means.

Design solutions of engineering systems can be visualised as a symbol structure with collection of instances that are related to one another in some manner. Consider the case of a building system. It can be visualised as a collection of two subsystems, viz., a lateral load-resisting system and a gravity load-resisting system. These two systems are independent of each other and have no direct relationship with one another. But they are the successors of the system *building*. Hence they are related through the parent system. Each of these subsystems can further be visualised as a collection of subsystems. The lateral load-resisting system can be a reinforced concrete (RC) rigid frame, consisting of many beams and columns. The objects beam and column can have their own generic symbol structure with different attributes. Each of these can have many instances representing individual beams and columns, which are semantically related to the generic symbol *beam* or *column*.

Engineering is a collection of a set of intelligent tasks, consisting of different activities such as planning, analysis, design, construction, management and maintenance. The five different manifestations of intelligence enumerated above are used at different stages of engineering of any system or artifact. Some typical instances in building engineering are presented below, in order to visualise the different situations that may arise requiring intelligent processing of information.

a) To respond to situations flexibly

During the planning stage of a building, the architect tries to generate the plan of a typical floor as a combination of different rooms or facilities. To begin with, only the area required for each facility, possibly the adjacency information among the facilities and the required orientation from the functional requirements are given. Any planning system first comes up with a plan, which may not fit into a proper shape and/or there may be voids in between. Now the system has to respond to this situation, which is going to be unique for different data sets, and generate decisions so that an acceptable plan is generated. This is a typical instance of an intelligent task, in which the system is expected to respond to situations flexibly.

b) To recognise the relative importance of different elements of a situation

There are many situations in a design process, where multiple solutions are generated, and it is required to select the *best* one from the alternatives. The system has to recognise the relative importance of the different solutions and then make a selection. Consider the following situation. Basic heuristics states that:

```
IF     number of stories < 15
THEN   provide RC rigid frame for lateral load resistance
IF     number of stories > 20
THEN   provide shear wall also along with RC rigid frame for
       lateral load resistance.
```

Now if the number of stories is between 15 and 20, other factors are also to be considered, such as wind zone, type of live load that is going to come on the floors, spacing of columns in the RC rigid frame etc., to decide whether shear wall is to be provided or not. The system has to recognise the relative importance of different scenarios and take an appropriate decision.

c) To find similarities between situations despite differences which may separate them

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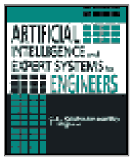

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Consider a situation where there are inclined columns in an RC rigid frame of a building system. The member design procedures to be adopted for these inclined beams are similar to those of columns, since all the columns are designed as beam-columns. The horizontal beams are designed only for flexure and not for any axial force, but inclined beams are to be designed as beam-columns. Despite differences in orientation, the similarity in structural behaviour requires the same member design methods for columns and inclined beams.

d) To draw distinctions between situations despite similarities which may link them

Such situations arise in the diagnosis of buildings in distress. For instance, two different buildings can show similar symptoms of distress. One cannot extend the diagnosis of the first situation to the second one also, because other factors such as soil conditions, quality of construction, design detailing etc. may be totally different in the two situations. Though the symptoms are similar, the system has to come out with the proper diagnosis, which may be different due to differences in other influencing factors.

The above illustrations presented a few instances when intelligent actions are required in engineering problem solving. The two important aspects to be considered to make the computer programs simulate intelligent problem solving are precise definition of the problem and systematic problem-solving techniques. The rest of this chapter focuses on these two aspects with emphasis on different search methods used for intelligent problem solving.

2.2 Problem Definition and Solution Process

The first task when solving any problem is the *precise definition of the problem* in terms of specifications for different situations during the solution process. The starting and the final situations form the core of problem definition. Specification defining the final situation constitutes acceptable solutions to the problem.

Once the problem is precisely defined, the next step is to *choose an appropriate solution technique*. For this, the problem has to be analysed to understand its important features and their influence on different solution techniques. It may be noted that though different solution techniques can be used to solve the same problem, one of them alone will solve it most efficiently.

All AI problems use knowledge to solve each task during problem solving and the solution process uses a control strategy to carry out the solution. As control strategies are generic and can be used to act on knowledge in different domains in different situations, it has to be separated from knowledge. The isolated domain *knowledge has to be properly represented*, so that it can be easily accessed and manipulated during problem solving.

Now *choose the most appropriate control strategy* and apply it to solve the problem for given situations. Solution of any AI problem follows the above-described four tasks [4–5].

To make a computer program work in an intelligent manner, the program has to simulate the intelligent behaviour enumerated as five distinct features in the earlier section. One way this can be achieved is by matching patterns and then deducing inferences. For this, the knowledge has to be represented as patterns of entities. Appropriate patterns have to be selected, matched with existing patterns and then decisions are to be made for further selection and matching. This process continues until a predefined final situation (goal situation) is arrived at. Matching patterns can result in either success or failure. A success will add valid patterns defining the current state of the problem being solved in a database. Further matching will be done with these patterns in the database. This leads to the fact that for both selection and matching, the solution process has to search for patterns both in the database of deduced patterns and in domain knowledge.

Thus the core of any AI program is the search through the knowledge. This is one striking difference between a conventional procedural program and an AI program. Thus to make an AI program efficient, the two basic components, viz., *knowledge representation schemes* and *control strategy for search* should be made most appropriate and efficient. Knowledge representation is elaborated in the next chapter on Knowledge-Based Expert System (KBES) and, hence, is not described here. The emphasis of this chapter is on the search techniques used in AI programs.

2.3 Production Systems

Production systems provide appropriate structures for performing and describing search processes. A production system has four basic components as enumerated below.

- A set of rules following the classical IF-THEN construct. If the conditions on the left-hand side are satisfied, the rule is fired, resulting in the performance of actions on the right-hand side of the rule.
- A database of current facts established during the process of inference.
- A control strategy which specifies the order in which the rules are selected for matching of antecedents by comparing the facts in the database. It also specifies how to resolve conflicts in selection of rules or selection of facts.
- A rule firing module.

Use of production system concepts for developing knowledge-based expert systems is dealt with in more detail in Chapter 3. Only the different search strategies generally adopted in AI programs are elaborated here.

2.4 Search Techniques

Typical AI problems can have solutions in two forms. The first one is a state, which satisfies the requirements. The second one is a path specifying the way in which one has to traverse to get a solution. A good search technique should have the following requirements.

- A search technique should be systematic
- A search technique should make changes in the database

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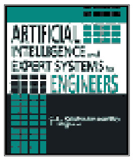

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Most AI books use the standard 8-puzzle problem to illustrate different search techniques. A simple search problem of configuration of bridge components is used here for better understanding of the working of different types of search techniques. The bridge configuration shown in Figure 2.1 has four components, viz., girder(G), deck(D), pier(P) and foundation(F). The components are represented by the letters G, D, P and F, respectively. An acceptable configuration is DGPF, showing the load flow pattern; i.e., load flows from deck to girder, girder to pier and pier to foundation. Any other sequence such as PDGF is not acceptable. The search is to arrive at an acceptable sequence, from a given initial sequence, say PDFG. Each of such sequences represents a state. PDFG is the given initial state and GDPF is the goal state. The search process has to carry out a search through the different states from the initial to the goal. Such searches are termed state-space-search, since they search in a space represented by different states which form solutions to a problem. To carry out the search, it is required to generate new states from the current state by applying some rules. The rule applied in the current problem is, swap two position values to generate a new state. For instance, DPFG, FDPG and GDFP are three states obtained by swapping the first position value with the other three values of the initial state PDFG. It should also be noted that the next swapping should not lead to the original values, which are already evaluated. The state space formed by all the possible 16 combinations along with the rules used for swapping position values are given in Figure 2.2. The root node of the tree is the given initial state. By swapping the values at the first position with the other three positions, three successor states of the state at root node are generated. The positions swapped to get each successor state are also shown in the figure. Each node at this level can have two successor nodes. The states at these nodes are generated by swapping values at positions such that the state at the parent node is not generated again. This process is repeated until all the possible combinations are generated.

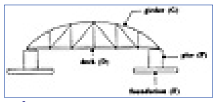


Figure 2.1 Components of a bridge system

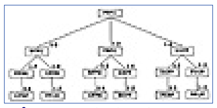


Figure 2.2 State space to be searched for the bridge problem

2.4.1 Breadth-First Search

The two most commonly used basic search techniques are Breadth-First Search (BFS) and Depth-First Search (DFS). Working of these two search methods are illustrated using the bridge component configuration problem shown in Figure 2.1. The state space to be searched is schematically represented and shown in Figure 2.2.

BFS is an easy search technique to understand. The algorithm is presented below.

```
breadth_first_search ()
{
   store initial state in queue Q
   set state in the front of the Q as current state ;
   while (goal state is reached OR Q is empty)
   {
           apply rule to generate a new state from the current
                   state ;
           if (new state is goal state) quit ;
           else if (all states generated from current states are
                     exhausted)
           {
                     delete the current state from the Q ;
                     set front element of Q as the current state ;
           }
           else continue ;
   }
}
```

The algorithm is illustrated using the bridge components configuration problem. The initial state is PDFG, which is not a goal state; and hence set it as the current state. Generate another state DPFG (by swapping 1st and 2nd position values) and add it to the list. That is not a goal state, hence, generate next successor state, which is FDPG (by swapping 1st and 3rd position values). This is also not a goal state; hence add it to the list and generate the next successor state GDFP. Only three states can be generated from the initial state. Now the queue Q will have three elements in it, viz., DPFG, FDPG and GDFP. Now take DPFG (first state in the list) as the current state and continue the process, until all the states generated from this are evaluated. Continue this process, until the goal state DGPF is reached. The order in which the states are generated and evaluated is shown in Figure 2.3. The 14th evaluation gives the goal state. It may be noted that, all the states at one level in the tree are evaluated before the states in the next level are taken up; i.e., the evaluations are carried out breadth-wise. Hence, the search strategy is called breadth-first search.

2.4.2 Depth-First Search

In DFS, instead of generating all the states below the current level, only the first state below the current level is generated and evaluated recursively. The search continues till a further successor cannot be generated. Then it goes back to the parent and explores the next successor. The algorithm is given below.

```
depth_first_search ()
{

   set initial state to current state ;
   if (initial state is current state) quit ;
   else
   {

      if (a successor for current state exists)
      {
            generate a successor of the current state and
                            set it as current state ;
      }
      else return ;
      depth_first_search (current_state) ;
      if (goal state is achieved) return ;
      else continue ;
```

```
        }
    }
```

Figure 2.4 shows the tree generated by the DFS for the bridge component configuration problem. The search reached the goal state after evaluating 11 states.

Since DFS stores only the states in the current path, it uses much less memory during the search compared to BFS. The probability of arriving at goal state with a fewer number of evaluations is higher with DFS compared to BFS. This is because, in BFS, all the states in a level have to be evaluated before states in the lower level are considered. DFS is very efficient when more acceptable solutions exist, so that the search can be terminated once the first acceptable solution is obtained. BFS is advantageous in cases where the tree is very deep. An ideal search mechanism is to combine the advantages of BFS and DFS. What is explained so far is unconstrained BFS and DFS. If constraints are imposed on the search, then the above algorithm needs to be modified. One such constrained DFS is described in Chapter 4, where multiple acceptable solutions for design problems are generated.

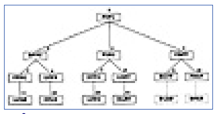


Figure 2.3 Sequence of nodes generated in BFS

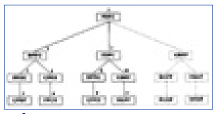
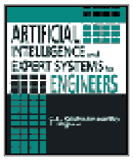


Figure 2.4 Sequence of nodes generated in DFS



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2.4.3 Heuristic Search

It can be noted that both these search methods are systematic and force mobility, which are primary requirements of any good search process. In the context of AI, many times one may not get the best solution. In such cases it is required to obtain a very good solution. A very good solution is not a best solution, but is an acceptable one. The introduction of 'heuristics' can improve the efficiency of the search process, possibly sacrificing the completeness. Heuristics generally guide the search process towards the region where the acceptable solutions lie. Heuristics to be adopted in a search generally depend on the problem being solved. For the bridge component configuration problem, how a heuristic can expedite the search is illustrated below.

The goal state DGPF gives us two important pieces of information. They are positions of each component and the sequence in which two components should appear in the solution. Let the initial state be PDFG and the three successors of this state are DPFG, FDPG and GDFP. When these states are evaluated using a heuristic based on the position values and sequences, the following deductions can be drawn.

DPFG : one position correct (D); no sequence correct

FDPG : one position correct (P); no sequence correct

GDFP : no position correct; no sequence correct

Since the first two states evaluate to the same level, either of them can be considered for the next evaluation. Let us take the second state FDPG. The two successors of this state are DFPG and GDPF. The evaluation of these states based on the heuristic gives:

DFPG : two positions correct (DP); no sequence correct

GDPF : two positions correct (PF); one sequence correct

The heuristic shows that the second state is closer to the goal state compared to the first. Hence consider the second state for evaluation. The only successor for this state is DGPF, which is the goal state. Hence, the search is terminated. From this it can be seen that when a simple heuristic is combined with BFS, the efficiency of the search improved resulting in only 7 evaluations to reach the goal state as shown in Figure 2.5. Indeed the number of evaluations would have been more, if DPFG was considered at the first level instead of FDPG.

Such heuristics can be represented as constraints and the search becomes constrained BFS or DFS search.

Heuristics cannot be generalised, as they are domain specific. Production systems provide ideal techniques for representing such heuristics in the form of IF-THEN rules. Most problems requiring simulation of intelligence use heuristic search extensively. Some heuristics are used to define the control structure that guides the search process, as seen in the example described above. But heuristics can also be encoded in the rules to represent the domain knowledge. Since most AI problems make use of knowledge and guided search through the knowledge, Rich and Knight [1] defines AI as *the study of techniques for solving exponentially hard problems in polynomial time by exploiting knowledge about problem domain*.

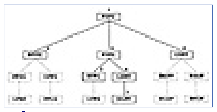
Figure 2.5 Sequence of nodes generated in the heuristic search

To use the heuristic search for problem solving, Rich and Knight [1] suggests analysis of the problem for the following considerations.

- Decomposability of the problem into a set of independent smaller subproblems.
- Possibility of undoing solution steps, if they are found to be unwise.
- Predictability of the problem universe.
- Possibility of obtaining an obvious solution to a problem without comparison to all other possible solutions.
- Type of the solution: whether it is a state or a path to a state.
- Role of knowledge in problem solving.
- Nature of solution process: with or without interacting with the user.

The general classes of engineering problems such as planning, classification, diagnosis, monitoring and design are generally knowledge intensive and use a large amount of heuristics. Depending on the type of problem, the knowledge representation schemes and control strategies for search are to be adopted. Combining heuristics with the two basic search strategies alone are discussed above. There are a number of other general purpose search techniques which are essentially heuristics based. Their efficiency primarily depends on how they exploit the domain-specific knowledge to eliminate undesirable paths. Such search methods are called ‘weak methods’, since the progress of the search depends heavily on the way the domain knowledge is exploited. A few of such search techniques, which form the core of many AI systems, are briefly presented here.

2.4.4 Generate and Test

This is simplest of all the problem-solving approaches. The algorithm is presented below:

```
generate_and_test ()
{
  begin:
  generate a possible solution ;
  evaluate the solution by comparing it with the
  given acceptability criteria ;
  if (solution satisfies the acceptability criteria) quit ;
  else go to begin ;
}
```

This is a brute-force method, which carries out an exhaustive search of the problem space. The generation of solutions can be either random or in a systematic manner. Adoption of systematic generation of solutions can make the search process more efficient. One such method is hill climbing. In hill climbing, feedback from the evaluation (test) is used to generate the next solution. In generate-and-test, the test function used to evaluate the solution just says whether the solution is acceptable or not. But in hill climbing, the test function also specifies how close the solution is to the goal state. In cases where the goal state cannot be specified a priori, the search is terminated when no further moves can be made. Hill climbing is very much similar to gradient-based optimisation techniques using mathematical programming, in which the test function is nothing but the objective function and gradient information is used to decide the direction for the next move.

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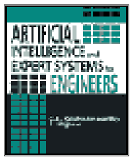

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2.4.5 Best-First Search

This method combines the advantages of the DFS and BFS methods. In this method, a single path is followed at a time, but paths are switched when more-promising paths than the current one are found. This is illustrated using the bridge components configuration problem. To some extent, it is similar to the heuristic search described above. But instead of using a qualitative heuristic, the evaluation of steps is quantified.

For evaluation of a state the following criteria are adopted, which is little different from the heuristic used earlier. A weightage of 100 is assigned to a state for each of the correct position values. This results in a weightage of 400 for the goal state, since all four components are in their respective positions. In addition to this, weightages of 100 are assigned for getting a correct position after a swap. The three successors of the initial states are generated and their scores are evaluated. The scores evaluated are given in Figure 2.6. For the first successor node, a score of 100 is obtained. Since none of the components is in the correct position, 0 weightage is assigned from the first criterion. Three possible paths can be generated from this state by swapping the first component with the 2nd, 3rd and 4th. First swapping will bring D to the first position, which is a correct one; hence a value of 100 is assigned. The second and third swappings will not bring any of the components to the correct positions, resulting in no additional weightages. Hence the score for the state DPFG becomes 100. Similarly the second state FDPG gets a score 300 and the third stage GDFP gets a score 100.

The scores indicate that the state FDPG is more promising for further exploration than the other two; hence it is pursued. Generate the two successors of FDPG, viz., DFPG and GDPF. The evaluation assigns weightages 200 for DFPG and 300 for GDPF. Hence select GDPF for further exploration. The only successor of GDPF is DGPF, which is the goal state. The complete tree generated after the search is shown in Figure 2.6. The goal state is arrived after 7 evaluations, which is same as in the case of heuristic search. But the selection criteria is quantified here and there was no conflict at the second level. It may be noted that each of the paths forms an alternate search path for solution of the problem. Hence, the tree is called an *OR Graph*. The best-first search is a simplification of A* algorithm originally presented by Hart et al. [6].

2.4.6 Agenda-Driven Search

Agenda-driven search is an improvement on the best-first search. In best-first search, only a queue is used to record the states being evaluated or the path traversed. But in agenda-driven search the queue is replaced by an agenda, which has a list of tasks that a system could perform. Each task in the agenda is associated with two items: justification for the task (the reason why a task is proposed) and a rating representing the usefulness of the task. The tasks are generally stored in the agenda in the order of their ratings. The search process can create new tasks or modify the rating of existing tasks. In such cases, as and when new tasks are created or ratings are modified, they are inserted at proper places in the agenda. As AI programs become large and more complex having a number of knowledge sources and requiring different reasoning strategies for different knowledge sources, techniques such as agenda-driven search become very useful and handy.

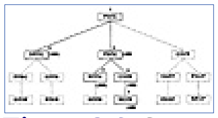
Figure 2.6 Sequence of nodes generated in BFS

2.5 Problem Decomposition and *AND-OR* Graphs

When a problem become large, the law is *divide and conquer*. The problem is decomposed into subproblems one level after the other until the subproblem at the lowermost level is trivial and easy to solve. Solutions to such subproblems are combined at appropriate levels to obtain a solution to the problem in total. Thus the problem decomposition or problem reduction simplifies the solution process. The graphs or trees generated by reducing such problems are called AND-OR graphs. Such graphs can have both AND nodes and OR nodes. One AND node may point to any number of successor nodes, all of which must be resolved in order to prove the AND node. But it is also possible to represent alternative solution paths from a node, similar to the case of an OR node. This implies that a node can have both AND and OR paths. Such a structure is called an AND-OR graph or tree. A typical AND-OR node is shown in Figure 2.7. The node represents a goal: *load bearing IS by RC rigid frame*. There are two alternative paths to reach the goal. If successor 1 is satisfied, then the goal is TRUE; or if both successors 2 and 3 are satisfied, then also the goal is TRUE.

Figure 2.7 Typical AND-OR node

The knowledge base in a KBES can be represented as an AND-OR graph, combining many AND-OR nodes. Typical knowledge nets, which are combinations of AND-OR nodes are presented and are explained in the next chapter. The knowledge contained in an AND-OR graph can be conveniently represented using production rules having the well-known IF-THEN construct. The search methods described so far, viz., BFS, DFS, best first search etc., cannot be directly used for searching for a solution in an AND-OR graph. Other appropriate techniques have to be used to search the AND-OR graphs. The AO* search algorithm is one popular algorithm generally used to generate solutions in an AND-OR graph [1]. Problems such as classification, diagnosis, monitoring etc. are represented using AND-OR graphs for solution. In such problems, the path from an initial state to the goal state forms a solution. Two most popular search techniques, backward chaining and forward chaining, in AND-OR graphs are presented in Chapter 3. Hence they are not described here.

Problem classes such as planning and design can be viewed as problems of constraint satisfaction. In such problems it is required to arrive at a problem state satisfying a given set of constraints. To do this, the available constraints are propagated to the extent possible. If a solution is obtained in this process, then the search is terminated; else a local search is carried out for further exploration.

In addition to the search techniques described above, there are a number of other search methods such as simulated annealing, genetic algorithms etc. They are not presented here as they are beyond the scope of this chapter.

This chapter presented an introduction to AI problems and a few important search techniques commonly used to solve AI problems. These search techniques are used in development of different generic problem-solving techniques such as KBES, design synthesis, case-based reasoning etc. which are dealt with in detail in the following chapters.

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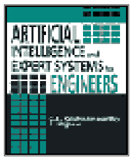

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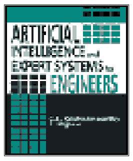

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Chapter 3
Knowledge-Based Expert System

3.1 Introduction

The Knowledge-Based Expert System (KBES) is the first realisation of research in the field of Artificial Intelligence (AI), in the form of a software technology. For developers of application software, particularly in medical and engineering disciplines, it was a boon, as it addressed the decision-making process with the use of symbols rather than numbers. Tasks belonging to the classification and diagnosis category were the first to benefit from the emergence of KBES technology. Though AI researchers were carrying out symbolic processing much earlier, the results of such research could be taken from *lab to field* only when KBES was introduced as a software tool for addressing a class of problems that required simulation of the knowledge-based decision-making process.

A number of articles appeared in many journals, technical papers were presented in conferences and books appeared in the market on this topic in the late 1970s and early 1980s [1–5]. In addition to these, a number of articles appeared in different journals specifically on the two expert systems, viz., MYCIN and DENDRAL. These gave an insight into the anatomy of KBES and its working [6,7]. A number of leading researchers, who were responsible for the realisation of this technology, worked for the development of these systems. Researchers working in the area of Computer-Aided Engineering (CAE) in many leading universities showed an active interest in further development of this technology by exploring its different aspects and applicability to different fields of engineering [8–13]. Later a number of researchers all over the world joined the fray in carrying out research and development to take this technology forward and to make it more useful for problem solving. As a result of all these developments, industries started realising the potential of the technology and have since moved in the direction of taking the prototype systems from lab to full-fledged working systems in the field. This chapter presents the technology of KBES, its architecture, the description of its components, problem-solving methodologies with illustration and application development. The AI search techniques and the related concepts such as problem reduction, AND-OR graphs etc., presented in Chapter 2 are elaborated here and their use in designing and developing expert systems is presented in this chapter. An expert system development environment DEKBASE is presented at the end of the chapter, which will give the readers a deep insight into the different aspects of the expert system development process.

3.2 What is KBES?

KBESs are computer programs designed to act as an expert to solve a problem in a particular domain. The program uses the knowledge of the domain coded in it and a specified control strategy to arrive at solutions. As knowledge base forms an integral, but implicitly understood part of a KBES, the adjective knowledge-based is often not used. The terms *expert system* and *knowledge-based expert system* can therefore be used interchangeably. An expert system is not called a program, but a system, because it encompasses several different components such as knowledge base, inference mechanisms, explanation facility etc. All these different components interact together in simulating the problem-solving process by an acknowledged expert of a domain.

A close examination of any decision-making process by an expert reveals that he/she uses facts and heuristics to arrive at decisions. If the decision to be made is based on simple established facts using a heuristic such as a rule of thumb, then it may be a trivial process. For instance, if the span of a beam is 12 feet, then the depth of the beam is fixed as 12 inches. Here the fact used to take the decision is *span of beam is 12 feet* and the heuristic used is *provide one inch depth for each foot of span* or, in other words, *depth of beam = span/12*. The solution obtained for a case of a 12-foot span is acceptable. But the heuristic cannot be blindly applied in all cases. Consider a span of 4 feet. A beam with a depth of 4 inches is not acceptable because a beam should have some minimum depth. Similarly a beam cannot be excessively deep, due to many considerations. Hence, while using the above heuristic, the engineer also checks for other conditions so that the solution obtained is acceptable. An expert system simulates such decision-making processes using the available facts and knowledge. More than one unit of knowledge is required for the above decision-making process. In addition to the knowledge contained in the heuristic, limiting conditions on the depth are to be checked, which the engineer knows from his experience or based on provisions given in design codes. Essentially a KBES works the way the decision is made in the above case. Let us try to understand the different components of the system with the above simple problem as an illustrative example. The following is a formal representation of the steps followed for the decision making.

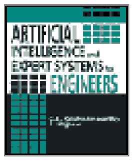
1. Obtain span of the beam
2. Use the heuristic and arrive at value for depth of beam
3. Check the value obtained for beam depth for any violation of acceptable values

The components of a knowledge-based decision-making system can be identified from the above statements. We have used two entities, viz., *span of beam* and *depth of beam*. When appropriate values are assigned to these entities, they become facts. For example, *span of beam = 12 feet* is a fact. The heuristic uses this fact to arrive at a value for the entity *depth of beam*. The heuristic can be formally written in the following manner.

```
IF      span of beam is known
THEN    depth of beam is (span of beam/12)
```

The heuristic written above using the well-known IF-THEN construct contains the knowledge required to take the decision on depth of beam. The decision obtained is incomplete, unless it is verified for a valid range as described. Two other statements using the same IF-THEN constructs can be written to represent the knowledge required for such verification.

```
IF      depth of beam < 9 inches
THEN    limit the depth of beam to 9 inches
IF      depth of beam > 3 feet
THEN    limit the depth of beam to 3 feet
```



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It may be noted that the heuristic type of knowledge and other rules of thumb or guidelines specified in design codes can very well be represented in the form of IF-THEN constructs called *production rules*. Not only are they easy to understand, but their representation is also very simple thus resulting in an easy implementation in a computer. Based on the above, the main two components of an expert system can be identified as:

Knowledge Base	Collection of knowledge required for problem solving
Control Mechanism	Checks the available facts, selects appropriate knowledge source from knowledge base, matches the facts with the knowledge, and generates additional facts

Only three production rules are used to represent the knowledge in the above illustration. But as the problem grows, more and more facts have to be generated based on already established facts. For example, after establishing the depth of beam, if one wants to check the available clear headroom, an additional source of knowledge is required, which can also be represented in the form of rules. Thus in an application, decisions are made or facts are established in a sequential manner, using already established facts. This process of using current facts and knowledge contained in the knowledge base to establish additional facts or decisions continues as a chain, until a fact specified as a goal is established. The control mechanism primarily carries out symbolic processing called inference. There can be a number of different ways in which the knowledge contained in the rules can be used for inference. Hence, the control mechanism can consist of many different inference strategies. Thus these two - *knowledge base* and *inference mechanisms* - form the main components of a KBES.

3.3 Architecture of KBES

As described in the previous section, a knowledge base and an inference engine consisting of one or more inference mechanisms form the major components of an expert system. When an expert system starts the process of inference, it is required to store the facts established for further use. The set of established facts represents the *context*, i.e., the present state of the problem being solved. Hence, this component is often called *context* or *working memory*.

Whenever an expert gives a decision, one is curious to know *how* the expert arrived at that decision. Also, when the expert prompts for information or data, one would like to know *why* that piece of information is required. The expert uses the knowledge he/she has and the context of the problem to answer the queries such as *how a decision is arrived at?* or *why a data is needed?* A separate module called an *explanation facility* simulates the process of answering the *why* and *how* queries. This module also forms an integral part of any expert system.

The process of collecting, organising and compiling the knowledge and implementing it in the form of a knowledge base is a labourious task. It does not end with the development of the system. The knowledge base has to be continuously updated and/or appended depending on the growth of knowledge in the domain. A knowledge acquisition facility, which will act as an interface between the expert/knowledge engineer and the knowledge base, can form an integral component of an expert system. As it is not an on-line component, it can be implemented in many ways.

A user of the expert system has to interact with it for giving data, defining facts and monitoring the status of problem solving. Conveying of information, be it textual or graphical, to the user should also be done in a very effective manner. Thus, a user-interface module with the capability to handle textual and graphical information forms another component of the expert system. Figure 3.1 shows the architecture of a KBES with its components and the way the components interact with each other.

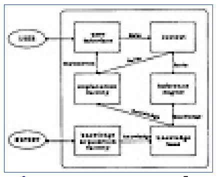


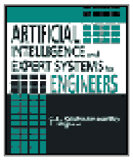
Figure 3.1 Architecture of a KBES

As seen so far, the knowledge base and the inference engine are the most important components in a KBES. Hence, a detailed look at these are required for better understanding of the technology. The following sections present a detailed description of the knowledge base and inference mechanisms.

3.3.1 Knowledge Base

The knowledge base contains the domain-specific knowledge required to solve the problem. The knowledge base is created by the knowledge engineer, who conducts a series of interviews with the expert and organises the knowledge in a form that can be directly used by the system. The knowledge engineer has to have the knowledge of KBES technology and should know how to develop an expert system using a development environment or an expert system development shell. It is not necessary that the knowledge engineer be proficient in the domain in which the expert system is being developed. But a general knowledge and familiarity with the key terms used in the domain is always desirable, since this will not only help in better understanding the domain knowledge but will also reduce the communication gap between the knowledge engineer and the expert. Before deciding on the structure of the knowledge base, the knowledge engineer should have a clear idea of different knowledge representation schemes and the suitability of each under different circumstances.

The knowledge that goes into problem solving in engineering can be broadly classified into three categories, viz., compiled knowledge, qualitative knowledge and quantitative knowledge. Knowledge resulting from the experience of experts in a domain, knowledge gathered from handbooks, old records, standard specifications etc., forms compiled knowledge. Qualitative knowledge consists of rules of thumb, approximate theories, causal models of processes and common sense. Quantitative knowledge deals with techniques based on mathematical theories, numerical techniques etc. Compiled as well as qualitative knowledge can be further classified into two broad categories, viz., *declarative knowledge* and *procedural knowledge* [14]. Declarative knowledge deals with knowledge on physical properties of the problem domain, whereas procedural knowledge deals with problem-solving techniques.



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Development of an expert system in an engineering domain would require use of all these forms of knowledge. Of course, it is the application domain that determines the nature of knowledge that goes into it. Consider, for instance, the domain of diagnosis for distress in buildings. It is required to find out how a crack is formed on the brick wall of a building. To arrive at the causes for the crack, the system should have knowledge about the position of the wall, the type of wall (load bearing, infill or partition), the thickness of the wall, the proportion of the mix used for mortar, the type of construction of the building etc. Depending on the type of wall, knowledge on foundation,soil type, design details of beams and columns in the floor etc. are required. In addition to the above, knowledge on how to use the available information to deduce the reasons for the crack is also required. The first part of the knowledge (declarative knowledge) mentioned above describes the scenario, whereas the second part of the knowledge describes how to use the knowledge (procedural knowledge) to arrive at the decision. Thus for the development of a KBES, one should know the different knowledge representation schemes and the possible modes of interaction between them.

Developing an expert system involves tasks such as acquiring knowledge from an acknowledged domain expert, documenting it and organising it, generating a *knowledge net* to check the relationships between different knowledge sources, checking for consistency in the knowledge and finally transforming the *knowledge net* into a computer program using appropriate tools. Such a program, called an expert system, is a formal system for storing facts and their relationships and the strategies for using them. In general, an expert system has knowledge about physical objects, relationships among them, events, relationships among events and relationships between objects and events. In addition, required types of search mechanisms must be represented to drive the system. Depending on the type of problems, other types of knowledge, such as time relationships, uncertainty levels of facts and assertions, performance levels, difference in behaviour of objects in different situations, assumptions, justifications, knowledge about knowledge (meta knowledge), additional explanations on facts and relationships etc., have to be represented. It points to the fact that formalisation of knowledge and problem-solving strategies forms a major part in expert systems development. The same piece of knowledge can be represented using more than one formal scheme, but with varying degrees of difficulty. The difficulty is not in the representation of the knowledge, but in its usage. The decision on selection of a scheme primarily depends on the type of application being built. Also, different knowledge representation schemes can be adopted for developing one application. The knowledge engineer has to decide which portion of the knowlege should be represented in what form, depending on the nature of the knowledge and the efficiency of its use. The most common methods of knowledge representation are:

1. Predicate logic

2. Production rules
3. Frames (objects) and semantic networks
4. Conventional programs

Predicate Logic

Predicate logic provides mechanisms for representation of facts and reasoning based on syntactic manipulation of logic formulae. It uses predefined rules of inference for assertion or deduction of facts. In the first-order predicate logic, the formulae are manipulated purely based on their form or structure. The major disadvantage of this scheme is that it cannot consider the meaning or semantic content of the formula. For better understanding of the concept, consider the following example. Consider a bridge system consisting of two girders and three piers as shown in Figure 3.2.

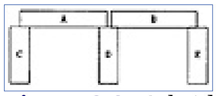

Figure 3.2 A bridge configuration with two girders and three piers

The following statements can be written to state the facts regarding the bridge system.

A is-a girder;	B is-a girder;	
C is-a pier;	D is-a pier;	E is-a pier;
C supports A;	D supports A;	
D supports B;	E supports B;	

In this, the terms *is-a* and *supports* are called predicates and A, B, C, D and E are called symbols. The *triplets* given above are called sentences. An inference rule is specified as given below:

If *x supports y* then *x gets-load-from y*

Another predicate gets-load-from is introduced in the inference rule. Any symbol of proper type can be substituted for the place holders x and y for assertion of facts. Using the given inference rule, the following facts can be asserted.

C gets-load-from A;	D gets-load-from A;
D gets-load-from B;	E gets-load-from B;

In predicate logic, all deductions are based on logic statements, and inference rules are guaranteed to be correct. In addition, a logic program will generate all possible inferences that can be drawn from the facts and rules. Though such predicate logic systems deduce all possible facts, their ability to carry out a constrained search through the facts and inferences is limited. This is primarily due to their inability to carry out guided search and also to represent search strategies. As new facts are generated, the inference rules are applied to assert newer facts. This process continues leading to combinatorial explosion until a goal state is reached. Only a constrained assertion of facts can improve the situation, which is difficult in predicate logic. In addition, predicate logic systems try to apply all the inference rules to all the facts. There is no mechanism to group facts and associate specific inference rules to different groups. Even in a small real-life AI-based system, there can be a number of facts and inference rules. Due to the above-mentioned limitations, it becomes difficult to apply predicate logic-based knowledge representation in expert systems. A good knowledge representation scheme should have the capability to represent real-life situations (objects and relationships among them), which can be exploited by efficient guided search strategies and which better reflect the way humans perceive and think.

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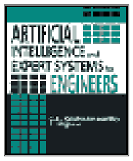

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Production Rules

Production rules are simple but powerful forms of knowledge representation providing the flexibility of combining declarative and procedural representation for using them in a unified form. A production rule has a set of *antecedent*s and a set of *consequents*. The *antecedents* specify a set of conditions and the *consequents* a set of actions. A few typical rules are given below:

1.	IF	span of beam is known
	THEN	depth of beam is (span of beam/12)
2.	IF	flow is open channel flow
	AND	Froud number > 1
	THEN	flow is supercritical
3.	IF	flow is open channel flow
	AND	Froud number = 1
	THEN	flow is critical
4.	IF	the object has two openings
	AND	opening at top is larger than that at the bottom
	AND	enough space is available on left side
	AND	space available on right side is too small
	THEN	take the pipe by the left side of the object
	AND	take pipe into the object from top opening

The conditions specified in rules 1 and 2 are very simple, but those in rule 3 are complex. A value assigned to a variable can be used to represent facts in the first two rules. But in the case of rule 4, physical objects and their properties have to be defined to represent facts, which cannot be done just by a *variable-operator-value* triplet. In all the above cases, when the IF portion of a rule is satisfied by the facts stored in the context or fact established by a user input, the actions specified in the THEN portion are performed, and the rule is then said to be fired. The knowledge stored in rules can be schematically represented in the form of a network. Two rules are represented in the knowledge net shown in Figure 3.3. One rule can be formed by considering nodes 1, 3 and 4, which is the rule 2 given above. The other rule can be formed by considering nodes 2, 3, and 4.

Typically a knowledge base will consist of a large number of rules. Logically the rules can be grouped into different rule bases. A knowledge net representing the set of rules in a rule base should be complete with proper connectivity of nodes in the net. Hence, drawing the knowledge net gives the knowledge engineer an opportunity to verify the knowledge base for possible inconsistencies and redundancies.

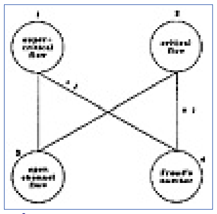

Figure 3.3 Representation of rules in net form

The knowledge net shown in Figure 3.4 represents the eight rules given in the knowledge base, that is given below. The domain is selection of a structural system and a floor system for multistory buildings. (The rules are written following the syntax of DEKBASE, an expert system development shell, which is explained in detail in Appendix I.) A rule set with very simple rules is selected for the purpose of illustration. The knowledge contained in the rules is very limited and incomplete.

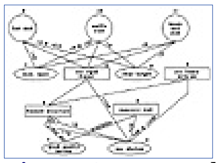

Figure 3.4 Knowledge net

```
TITLE  Rules for Selecting Structural System

GOAL   floor system

RULE   SSS_1
IF     no of stories <= 5
AND    good quality bricks IS available
THEN   load bearing IS by masonry wall

RULE   SSS_2
IF     no of stories <= 5
AND    good quality bricks IS not available
THEN   load bearing IS by rcc framed structure

RULE   SSS_3
IF     no of stories > 5
THEN   load bearing IS by rcc framed structure

RULE   SSS_4
IF     load bearing IS by rcc framed structure
AND    no of stories <= 20
THEN   structural system IS rcc rigid frame

RULE   SSS_5
IF     load bearing IS by rcc framed structure
AND    no of stories > 20
AND    no of stories <= 35
THEN   structural system IS rcc frame with shear wall

RULE   SSS_6
IF     structural system IS rcc rigid frame
AND    maximum span in M < 10
AND    clear height in M < 3
AND    clear height in M > 2.5
THEN   floor system IS flat slab
```

```
RULE   SSS_7
IF     structural system IS rcc rigid frame
AND    maximum span in M > 8
AND    maximum span in M < 20
AND    clear height in M > 3
THEN   floor system IS waffle slab

RULE   SSS_8
IF     structural system IS rcc rigid frame
AND    maximum span in M < 8
AND    clear height in M > 3
THEN   floor system IS beam and slab
```

The knowledge net represents the schematic diagram of the knowledge base. There are 11 nodes in the knowledge net. As the knowledge given is only a portion of a large knowledge base for selection of structural systems and preliminary dimensioning of structural elements in multistory buildings, further knowledge for dimensioning of shear wall (node 5) and load bearing by brick wall (node 3) is not included. There are two rules for deducing load bearing by an rc frame. Hence, node 4 is made an OR node with two different sets of conditions. Unless otherwise specified all other nodes except 1, 2, 7 and 8 are AND nodes. Nodes 1, 2, 7 and 8 represent initial states; i.e., the user has to give data for establishing facts represented by those nodes. The nodes 9, 10 and 11 represent different states of the same variable and are the goal nodes implying that the inference will terminate once the process reaches one of these nodes. The use of knowledge contained in the knowledge base for decision making is explained in detail in the section on inference mechanisms.

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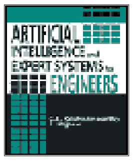

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It is a common practice in the development of expert systems to logically divide the rules into smaller rule bases and to control from a higher-level rule base which has knowledge about the different rule bases in the knowledge base. If there are more than one rule bases, each of them should have separate contexts. The higher-level rule base having meta rules will control the overall inference process and will have a global context. The inference engine of the expert system shell should properly handle different contexts for proper solution of the problem. To illustrate the use of meta-level knowledge bases, a second rule base having three rules is presented below, which arrives at the span-to-depth ratio for beams based on the number of stories in the building.

```
TITLE  Rules for obtaining beam depths
GOAL   span to depth ratio

RULE Beam 1               IF    no of stories <= 5
                          THEN  span to depth ratio = 15

RULE Beam 2               IF    no of stories > 5
                          AND   no of stories <= 8
                          THEN  span to depth ratio = 12

RULE Beam 3               IF    no of stories > 8
                          THEN  span to depth ratio = 10
```

Now the inference process has to invoke this rule base only if the floor system selected is beam and slab. A meta-level rule base is written which initiates the overall inference process. The meta-level rule base for this case is given below.

```
TITLE  Rules for controlling inference
GOAL   inference completed

RULE   Meta 1
IF     floor system selection completed
AND    beam depth ratio is required
```

```
OR      beam depth ratio is not required
THEN    inference completed

RULE    Meta 2
IF      NOT floor system IS_DEFINED
THEN    LOAD SSS
AND     floor system selection completed

RULE    Meta 3
IF      floor system IS beam and slab
AND     NOT span to depth ratio of beams IS_DEFINED
THEN    beam depth ratio is required
AND     LOAD BEAM
AND     beam depth ratio obtained

RULE    Meta 4
IF      NOT floor system IS beam and slab
THEN    beam depth ratio is not required
```

The rules in the above rule base are meta rules; i.e., they have knowledge about the other two rule bases. In the above meta rule base the variables ‘floor system’ and ‘span to depth ratio of beams’ are defined as global variables. In their respective rule bases also they are defined as global variables, thereby defining the scope across its own rule base and meta rule base. The process of inference and control of the overall inference process by the inference engine are illustrated in the section on inference mechanisms.

Frames (Objects) and Semantic Networks

Objects are very powerful forms of representing facts in expert systems. They are ideally suited for representation of declarative knowledge, which describes physical entities and semantic relationships between them. Any engineering activity is centered around an artifact or a facility, and detailed information about the artifact is required to make decisions concerning it. Different attributes of the artifact may be used at different stages of a problem such as planning, analysis, detailing, manufacturing/construction etc. Hence, it is appropriate to use objects with attributes encapsulated in order to have a more-structured representation of facts in the context, during execution of the expert system. Also, the rules should be able to interact with the objects. For instance, the rule that we wrote earlier can be written as:

```
IF      beam.span is known
THEN    beam.depth = beam.span/12
```

In the above rules, the object beam and its two attributes are used. As early as in 1975, Minsky introduced the concept of ‘frame’ to represent stereotyped situations. A frame is defined as a unit of a knowledge source described by a set of slots. The slots can be of two types, viz., abstract or concrete. This classification is made based on the type of information associated with them. A concrete slot would contain a specific value, such as ‘span of beam = 12’, i.e., a value 12 is associated with the slot ‘span’ of frame ‘beam’. An abstract slot would contain descriptions that characterise any possible value for the slot. For example, the slot ‘span’ of the frame ‘beam’ can have a description attached to it such as ‘get span from the slot bay-width of frame building’. Here no specific value is attached to the slot; instead the description given has to obtain a value as indicated. The description shown above can be implemented by attaching functions to the slots. Such functions are called ‘demons’. Demons are sleeping programs, which are invoked by some specific events. The working of demons is described later in the section on inference mechanisms.

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The slots in a frame can also be made relational in nature, wherein the slot contains information on the relationship of the frame with other frames. Consider for example, two frames ‘beam’ and ‘building’. The frame beam can have a slot ‘part-of’, which can take the value ‘building’, which is the name of another frame. Another frame beam_5 can have a slot ‘is-a’, which can take a value beam, which is also the name of a frame. The ‘is-a’ relationship implies that beam_5 is an instance of frame beam and beam_5 gets all the generic properties of the frame beam. Only values for specific slots are to be explicitly obtained. This concept is very much similar to ‘classes’ and ‘instances’ of object-oriented programming. The facility to have slots describing relationships with other frames provides a mechanism for defining networks of frames in the context, with links (relationships) described using semantics. Such networks are called semantic networks. They are very powerful in expressing the declarative knowledge about an artifact. A typical semantic network described using four frames is shown in Figure 3.5. Four frames, viz., bridge, deck, main-girder and main-girder_1 are shown in the figure with values attached to a few slots. Only a few typical slots are shown for each frame for the purpose of illustration. Consider the slot ‘span-lengths’. It is a multivalue slot, in which an array of values is attached to it, the first value being the length of span 1, the second for span 2 … etc. The first slot in the frame ‘deck’ is ‘part-of’ having value ‘bridge’, which is the name of another frame. It indicates that deck is part of bridge’. The two frames are semantically connected through the slot ‘part-of’. Similarly the frame main_girder also has a slot ‘part-of’ with value ‘deck’, implying that main_girder is a part of deck. Likewise examine the relationship between frame ‘main-girder’ and ‘main-girder_1’, These two are related through a slot ‘is-a’. This indicates that the frame ‘main-girder_1’ is an instance of frame ‘main-girder’. Since there are six main girders, the system has to generate six instances of the frame ‘main-girder’ and all the values common to the main girder are inherited by the instances from the generic frame. Only values which are specific to each instance are obtained through inference for respective instances.

Figure 3.5 A typical semantic network represented using frames

This illustrates how frames and semantic networks can be used to represent declarative knowledge in a domain. In expert systems developed for real-life applications, a combination of rules and frames is required to represent the domain knowledge.

Procedural Programs

Engineering problem solving involves numerical computations, in addition to inference using knowledge. In a real-life expert system, the system has to perform numerical computations at different stages of the solution process. The amount of computations may be very small in some cases and quite large in many cases. Based on the values inferred, a detailed analysis of the artifact may have to be carried out to evaluate the correctness of the parameters arrived at. The quantitative knowledge required for such computations can be represented as functions/programs written in high-level programming languages such as FORTRAN or C. An expert system should be able to call these programs as and when required during problem solving. Hence, they also form part of the knowledge base of the expert system.

Most expert system development shells provide facilities to represent knowledge in the three forms, viz., rules, frames and functions in procedural languages. The predicate logic form of knowledge representation is the natural form in Prolog, one of the specialised AI languages. Prolog provides predicate logic-based representation with backtracking inference, which is inadequate for developing large expert systems for practical applications.

3.3.2 Inference Mechanisms

Inference mechanisms are control strategies or search techniques, which search through the knowledge base to arrive at decisions. The knowledge base is the state space and the inference mechanism is a search process. As expert systems predominantly process symbols, the inference process manipulates symbols by selection of rules, matching the symbols of facts and then firing the rules to establish new facts. This process is continued like a chain until a specified goal is arrived at. In an expert system, inference can be done in a number of ways. The two popular methods of inference are backward chaining and forward chaining. Backward chaining is a goal-driven process, whereas forward chaining is data driven. Working of the methods is illustrated using a typical knowledge base presented in the previous section on knowledge representation. The knowledge base contains three rule bases, one for selection of a structural system, the second for arriving at span-to-depth ratios for beams and the third the meta rule base. The inference process for the first rule base is presented first for understanding the two methods, viz., backward chaining and forward chaining.

The knowledge net consists of 11 nodes (see Figure 3.4). Each node represents a state in the state space. Nodes 1, 2, 7 and 8 are initial states, since those states cannot be deduced based on any facts. The user has to supply data for establishing states represented by them, whereas all the other nodes represent states which are to be deduced based on already established facts. There are two paths for reaching node 4; i.e., there are two ways in which the state or fact represented by node 4 can be established. Hence, that node is represented as an OR node. The working of backward chaining with a goal to arrive at a floor system is described first.

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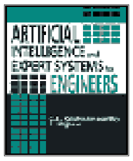

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Backward Chaining

As stated earlier, backward chaining is a goal-driven process. It tries to establish goals in the order in which they appear in the knowledge base. The goal variable defined in the rule base for selection of a structural system is ‘floor system’. The inference process will stop once this variable gets a value. The three dynamic data structures used during the inference process are working memory (context), a rule stack and a goal stack. Whenever any one of the actions of the inference process, viz., select, match and execute occur, one or more of these data structures get modified. Studying the effect of these actions on the data structures during the inference process is a better way of studying the mechanisms of inference processes. Hence, working of the inference process is described here through the changes that occur to the context, a rule stack and a goal stack. Rule stack and goal stack are temporary data structures created for bookkeeping. When the process starts, the context is empty and the goal variable is pushed to the goal stack. Then the process selects the first rule in the rule base with a goal variable in the THEN part and pushes it into the rule stack. In the present rule base, rule 6 is the first rule having the goal variable in the consequent. Hence, rule 6 is pushed to the rule stack and the goal variable to the goal stack. The status of the context, goal stack and rule stack at that instance is shown in Figure 3.6.

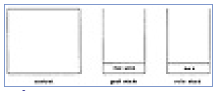

Figure 3.6 Status of context, goal stack and rule stack - I

It can be seen that rule 6 is the first rule having the goal variable ‘floor system’ in the consequent. Once the rule 6 is SELECTED, it starts MATCHING antecedents in the order in which they appear in the rule. The first condition is ‘structural system IS rcc rigid frame’. Matching of the rule can be pursued further only if this fact is established. Hence, the inference process sets the variable ‘structural system’ as the current goal. It is set by pushing it into the goal stack and also pushing the first rule in the list having the current goal variable in the THEN part into the rule stack. Thus rule 4 is selected for evaluation. The state of context and goal and rule stacks at this instance is shown in Figure 3.7.

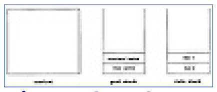

Figure 3.7 Status of context, goal stack and rule stack - II

Now the inference process starts checking the first condition of rule 4, which is ‘load bearing IS by rcc framed structure’. As a result, the variable ‘load bearing’ becomes the current goal and is pushed into the goal stack and the rule 1 is pushed into the rule stack. The status of context and rule and goal stacks at that instance is shown in Figure 3.8.

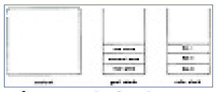
Figure 3.8 Status of context, goal stack and rule stack - III

The first condition of rule 1 is on ‘no of stories’, which is represented in the knowledge net by an initial state. Hence, there is no rule in the rule list with this variable in the THEN part, implying that the user has to supply the data for this variable. Let the user response to the query for this variable be 15. This response establishes the first fact and it is stored in the context. This results in the condition ‘no of stories <= 5’ to be FALSE and rule 1 cannot be fired and is discarded. This is done by popping the rule stack. The inference process takes the next rule with the same consequent (which is rule 2) and pushes it into the rule stack and starts evaluating the first condition in the antecedent. As that also evaluates to FALSE, rule stack is popped and the next rule with the current goal variable (‘load bearing’) in consequent (rule 3) is pushed to the stack. The condition in the antecedent is matched with that in the context and it evaluates to TRUE and the rule is fired. This establishes the current goal and the fact is stored in the context. As the current goal is established, and the rule is fired, both the rule stack and goal stack are popped. The status of the stacks and the context at this instance is shown in Figure 3.9.

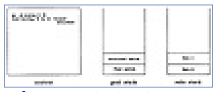
Figure 3.9 Status of context, goal stack and rule stack - IV

Now the current goal is the one which is on the top of the goal stack, i.e., ‘structural system’ and the current rule is rule 4. Both the conditions of this rule evaluate to TRUE by comparing them with the facts in context. This results in firing of the rule and the new fact established ‘structural system IS rcc rigid frame’ is added to the context. Both the stacks are popped and the current goal becomes ‘floor system’ and the current rule becomes rule 6, which are on top of the respective stacks. The first condition of the current rule evaluates to TRUE and the second condition is taken. As that variable is in an initial state in the knowledge net, the user is asked to provide a value for the same. Let the user response be 7. This results in evaluation of the condition to FALSE, the rule is rejected, and the rule stack is popped. The next rule with current goal variable in consequent is selected, i.e., rule 7, which is also discarded since the second condition evaluates to FALSE. Now the next rule (rule 8) is selected by pushing it into the rule stack. The first two conditions of the rule evaluate to TRUE and the user is prompted for the variable in the third condition. Let the user response be 3.2, which evaluates the condition to TRUE and the rule is FIRED. This results in getting a value ‘beam and slab’ for the goal variable. Since the rule is fired, both the stacks are pushed and the newly established fact is added to the context. Now both the stacks are empty and the inference process is completed. The status of context at this instance is shown in Figure 3.10.

Figure 3.10 Status of context, goal stack and rule stack - V

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The explanation facility of the expert system provides a mechanism for querying the context for getting the value of a variable (*what?*) and knowing how a fact is established (*how?*). The answer to the first query is directly obtained from the context, whereas the answer to the second query, i.e., *how*, requires reference to the knowledge base. The process associated with the query *how?* searches for the rule with the required fact in the THEN part and displays the rule, which shows how the fact is established. Obtaining an answer to a query *what if?* would be very useful, if the user of the system wants to experiment with the decision-making process, by modifying a user input. This can be done in two stages. First, those facts which are dependent on the modified variable have to be undone. Then they have to reestablished by continuing the inference process from that point. This is quite complex and requires maintenance of the complete line of reasoning with the dependencies of facts in the context. The inference process builds a complete dependency network based on TMS (Truth Maintenance System). This dependency network will help to backtrack from any stage to any previous stage by undoing the relevant actions, resulting in removal of many facts from the context. This backtracking continues until the establishment of a fact with the variable, the value of which is modified with the *what if* query. The inference process restarts from that point and continues until a final goal is established. Because of the difficulty involved in maintaining the dependency network of decisions made, many commercially available tools do not have this feature.

Forward Chaining

Forward chaining is a data-driven inference process. The user of the system has to give all the available data before the start of the inference. The inference mechanism tries to establish the facts as they appear in the knowledge base until the goal is established. Consider the same rule base. The user gives the available data and the state of the context before start of the inference as shown in Figure 3.11.

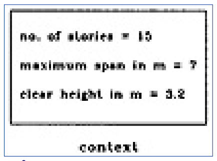

Figure 3.11 State of context before start of inference

The inference process selects the first rule in the rule base and discards it since the first condition itself evaluates to FALSE. Then it goes to the second rule, which is also discarded. The condition in the third rule evaluates to TRUE and it is fired resulting in a new fact being added to the context. Rule 4 is also fired, but discards 5, 6 and 7. Finally rule 8 is fired establishing the goal, which terminates the inference process. It so happened in the present case that in one iteration itself, the goal is established. In large rule bases, a number of iterations may be required before the goal is established. The order in which rules appear in the rule base plays a major role in the way inference is carried out in forward chaining, whereas such order does not play any role in backward chaining. But the order in which conditions are listed in a rule is important in backward chaining. The order in which questions are asked to the user for response depends on this order. Hence, before formulating the rule base, the knowledge engineer should decide whether backward chaining or forward chaining is going to be adopted for reasoning.

The third inference strategy is the hybrid inference mechanism. It is a combination of the backward and forward chaining process. Backward chaining is suitable, if there are few goal states and many initial states. The sequence in which the data are requested depends on the flow of the inference process. In forward chaining all the data that the user knows have to be given a priori and the system does not prompt for any data. If the data are sufficient the goal may be reached; otherwise it may exit stating that the goal is unreachable with the available data. Hence, the forward chaining process is suitable only when there are very few initial states and many goal states. In large expert systems, many initial and goal states can exist. Also the user may not be able to give all the necessary data a priori, as he/she may not be able to visualise the flow of the inference process. In this context, a hybrid inference mechanism seems to be suitable. It starts in the forward chaining mode with an empty context by trying to establish the facts as they appear in the rule base and then backward chains to prove or disprove them. The overall direction of the hybrid chaining process is forward with backward chaining being invoked as and when facts are to be established. The user does not give all the data a priori, but gives data as and when prompted for.

Large expert systems can have a number of rule bases and each one can have its own inference strategy within its scope. At the meta level also the knowledge engineer can select any strategy for reasoning. Inference with more than one rule base is illustrated with the three rule bases given in the previous section. Let the inference process start with the meta-level rule base and the strategy selected be backward chaining. The goal at the meta-level is ‘inference completed’. To prove this, the variable ‘floor system selection completed’ and either of the variables ‘beam depth ratio is required’ or ‘beam depth ratio is not required’ should evaluate to TRUE. Evaluation of the two variables to TRUE will ensure that the floor system is selected (by loading the rule base SSS and carrying out inference in that) and if the floor system selected is beam and slab, then the span-to-depth ratio is obtained (by loading the rule base BEAM and inferring with it). If the floor system selected is not beam and slab, then the rule base BEAM will not be loaded. This is ensured by introducing the additional variable ‘beam depth ratio not required’. The rules in meta-level rule base are also organised for backward chaining. The ordering of variables in the first rule is very important, which imposes the sequence in which other rule bases are to be loaded and inferred. Thus the complete problem-solving sequence with a number of rule bases can be effectively controlled using meta-level rules.

If frames are also used along with rules to represent knowledge, facts related to variables defined in frames are stored in a separate context called frame base. A frame base can have a number of frames defined in it, with a concrete or abstract type of slot. Frames can also be related using semantic relationships, which create semantic networks for representing declarative knowledge. But generally, chaining is done on rule base variables and not on the frame variables. Hence all the variables defining the inference process are to be defined as rule base variables.

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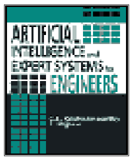

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Inference Using Knowledge in Frames

A number of different types of inferences can be achieved using the knowledge represented in frames. Those inferences will not generally form the control strategy for overall problem solving as in the case of rule base inference. But they demonstrate many intelligent features that human beings use in the process of problem solving. One such feature is simulation of common sense. An example is presented below, which illustrates simulation of common sense using frames.

Consider a situation, where someone tells you that *A is father of B* and *B is male*. Later a reference to *son of A* brings to your mind that *B is son of A*. No explicit statement is made at any time that *B is son of A*. But because of the common sense (based on knowledge you have on the relationship between parent and child) you are able to make a statement *B is son of A*. Similar situations, i.e., inference based on common sense, can be simulated in computer programs using techniques associated with frames and frame management. How this can be achieved is described below.

The two basic features of a frame management system are that frames are created during run time and that slots and values are added dynamically during the inference process.

Let *A* and *B* be two frames having two slots *name* and *father_of* for *A* and *name* and *sex* for *B*. Let the slot *name* be assigned respective names *A* and *B* and the slot *sex* of frame *B* be assigned a value *male*. Specifying a statement *A is father of B* is achieved by assigning a value *B* to the slot *father of* in frame *A*. A demon (procedure) of IF_ADDED type is attached to the slot *father_of* of frame *A*. This demon is activated, once a value is assigned to the slot. Figure 3.12 shows the state of the frame before activation of the demon.

When a value is assigned to the slot *father_of* of frame *A*, the demon attached to the slot gets automatically triggered, which adds a slot *son_of* to the frame *B* and assigns the value *A* to it. The knowledge of relationship is encapsulated in the demon attached to the slot Status of the frames after invocation of the demon attached to the *father_of* slot of frame *A* is shown in Figure 3.13.

Figure 3.12 Status of frames *A* and *B* before activation of demon

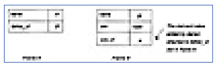

Figure 3.13 Status of frames *A* and *B* after activation of demon

The knowledge engineer who designs the knowledge base attaches the demon to the slot, which is automatically activated when the event of assigning a value of a slot occurs. This simulates inference based on common sense. The same effect can be achieved by attaching an IF_NEEDED demon to the *son_of* slot of frame *B*. This demon is invoked if a reference is made to the *son_of* slot of frame *B*. An advantage of this approach is that value is inferred and added to a slot only if a reference to the slot is made. Another type of demon is IF_DELETED. These types of demons are invoked if a slot is deleted from a frame. Such demons are very useful in many engineering problems, in which the contexts are to be updated during problem solving based on any modification in assumptions or based on some values computed. Many different types of such inferences can be simulated using the concept of demons. The facilities of the frame management system are described in detail later in the presentation of DEKBASE, an expert system development shell.

3.3.3 Inexact Reasoning

One of the most important capabilities of human experts and one of the most difficult to faithfully replicate in an expert system is the ability to deal with imprecise, incomplete and sometimes uncertain information. However, efforts have been made and techniques have been proposed by researchers working in the field, to incorporate inexact reasoning based on uncertain information in expert systems. Uncertainty is obviously present in most expert system algorithms because experts can rarely be sure of the statements they make. As the attention continues to shift to real-world problems of practical importance, however, it has become apparent that corresponding domain and problem knowledge is usually less than certain. On the other hand, the classical methods of forming inferences are derived from logic and use techniques such as resolution methods which deal with categorical information. Hence, the concern is how the uncertain knowledge can be used to find inferences that are well founded even if they are not categorical.

Uncertainty arises from various sources and in a variety of ways. Hence, the method through which the system handles uncertain information forms a critical component of its overall performance. The techniques that have been implemented in existing systems are all variations of a few major themes, with varying degrees of success.

Major sources of uncertain information in knowledge bases of expert systems can be the following: unreliable information, imprecise descriptive languages, inference with incomplete information and poor combination of knowledge from different experts [5].

1. Ill-defined domain concepts or inaccurate data lead to unreliable information. When an expert is unable to establish a concrete correlation between a rule premise and its conclusion, the resulting knowledge base suffers.

2. The ambiguities and impreciseness in the use of natural languages give rise to lack of precision during translation to a knowledge base. As a result the rules are not expressed precisely in a formal language that can be interpreted.

3. The inference carried out with incomplete information leads to establishment of incorrect facts and results in unacceptable decisions.

4. Involvement of more experts from the same domain can lead to disagreement between them and a consensus can lead to more confusion than correctness.

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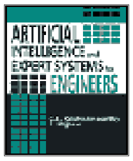

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This points to the fact that expert systems should have the capability to handle uncertainty as every domain contains information that is inherently inexact and incomplete. In processing such uncertainties in an expert system, what is primarily required is formal representation of the notion of uncertainty, quantification of degrees of belief, and a mechanism for reasoning under uncertainty. The best-known formalism for representing uncertainty is the probability theory. But the apparent practical difficulties in applying probability theory to model complexities of uncertain knowledge led to development of a variety of alternative methods. These include heuristic approximations to probability represented as certainty factors or confidence levels associated with facts, fuzzy set theory designed to handle linguistic imprecision, non-monotonic reasoning and default reasoning and interval representations as defined in Dempster-Shafer belief functions. None of these methods was without shortcomings. Their failure can either be because they were combined with simplified uncertainty propagation mechanisms or because they were axiomatically implied in contradiction with reality. Also, some of them are of an intuitive type and are difficult for mathematical manipulation.

Reasoning systems based on predicate logic are intellectually appealing and conceptually elegant as they are precise and rigorous. They work on the principle ‘using formal logic truth that can be derived with equal assurance’. Once established, truth is always true. Moreover, derived truth will never produce a contradiction, given no contradiction exists within axioms. These characteristics make predicate logic a monotonic reasoning system, implying that it continuously moves in one direction adding more truth. Although such monotonic reasoning systems are consistent and give reliable inference, their applicability to real-world problems is limited. The reasoning process required for inferring in practical situations which are generally unstructured must recognise the following facts.

1. At least at any given instance of the decision-making process, available information is incomplete;
2. Conditions can change over time;
3. There is a need to make an efficient, but possibly incorrect guess when reasoning reaches a dead end.

3.3.4 Non-Monotonic Reasoning

Beliefs play a major role in augmenting absolute truth, which can change when more facts are given. These beliefs, which are based on default assumptions, are made because of lack of evidence. A non-monotonic reasoning system includes a set of premises, which are to be immutably true. In addition to these truths, the system keeps a set of tentative beliefs, which are nothing but knowledge sources representing assumptions or facts inferred from the assumptions. For each such belief, the system maintains a dependency record that tracks a belief with its justification, which includes the facts, beliefs and inferences that were used to generate the tentative belief. A non-monotonic reasoning system allows addition of a new piece of knowledge or facts in the context, that can cause a previously believed tentative truth to become false. The belief revision mechanism propagates the effect of any change in belief through the use of dependency-directed backtracking.

Planning and design problems use a large number of tentative assumptions based on inexact or partial information. The non-monotonic reasoning system, which has a built-in mechanism through the dependency-directed backtracking, provides increased power and flexibility to solve such problems in a very effective manner. But its implementation requires a large amount of memory to store dependency information and a large amount of processing time to propagate changes in belief.

Doyle presented a TMS, an implementation of the non-monotonic reasoning system [15]. It maintains consistency in the knowledge base by calling the reasoning system as and when a new truth value is generated. It is to be noted that the role of TMS is passive, since it never initiates generation of inferences. When the TMS discovers an inconsistency in the current set of beliefs arising out of a newly added fact, it invokes dependency-directed backtracking to restore the consistency.

3.3.5 Reasoning Based on Certainty Factors

The first uncertainty management scheme was proposed by Shortliffe in the 1970s, which was tailored to be used with knowledge-intensive rule-based systems. The scheme got refined during the development of MYCIN, in order to overcome the weakness of the probability theory-based approaches. The certainty factor-based approach proposed and successfully implemented by Shortliffe is briefly presented below.

In expert systems using certainty factors, the knowledge consists of rules in the form “IF <evidence> THEN <hypothesis> CF”, in which CF denotes hypotheses belief given observed evidence. Before any combination of evidence can be performed, two intermediate functions must be calculated. These functions, *MB*[*h*,*e*] and *MD*[*h*,*e*], are measures of the degrees to which belief in a hypothesis would be increased if *e* were observed, and degree to which belief in *h* would be increased by observing the same evidence, *,e* respectively. The above definitions can now be specified in a formal manner in terms of conditional and a priori probability.

$$MB[h,e]=\begin{cases}1 & \text{if } P(h)=1\\ \dfrac{\max[P(h|e),\,P(h)-P(h)}{\max[1,0]-P(h)} & \text{otherwise}\end{cases}\qquad(3.1)$$

$$MD[h,e]=\begin{cases}1 & \text{if } P(h)=0\\ \dfrac{\min[P(h|e),\,P(h)]-P(h)}{\min[1,0]-P(h)} & \text{otherwise}\end{cases}\qquad(3.2)$$

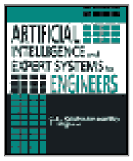
The values of *MB*[*h*,*e*] and *MD*[*h*,*e*] range between 0 and 1. If more pieces of evidence support a hypothesis, a combination function for *MB* and *MD* (indicating the total strength of hypothesis belief and disbelief). Evidence is then propagated by computing CF from *MB* and *MD*, in which

$$CF=\frac{MB-MD}{1-\min\left[MB,MD\right]}\qquad(3.3)$$

The value of CF can range from -1 to +1, -1 indicating confirmation of hypothesis negation and +1 indicating its confirmation. When two or more rules affect the same hypothesis, the individual CFs obtained from the rules are combined to form a common CF for the hypothesis.

$$CF_{combine}(x,y)=\begin{cases}X+Y(1-X) & \text{if } X \text{ and } Y>0\\ \dfrac{X+Y}{1-\min(x,y)} & \text{if any of } X,Y<0\\ -CF_{combine}(-X,-Y) & \text{if both } X,Y\geq 0\end{cases}\qquad(3.4)$$

Several expert systems have been built using the certainty factor approach, including MYCIN, a diagnostic program for infectious blood disease, SACON, a structural analysis consultant for finite element modelling. The certainty factor-based approach avoids the need for prior probability, thereby addressing one or more contentious challenges hurled at probabilistic belief propagation.



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A number of other techniques are also proposed by researchers to handle uncertain knowledge and carry out inexact reasoning. A few of them are subjective probability theory, Dempster-Shafer theory based on mathematical theory of evidence, belief functions, possibility theory as an extension of the theory of fuzzy sets and evidence propagation. As the objective of the present chapter is to give the reader an idea on the need for handling uncertainty in knowledge and a general approach to carry out inexact reasoning in KBES, detailed presentation of the above is not attempted. Also none of the schemes reported in the literature was without shortcomings. A complex uncertain reasoning mechanism necessarily involves additional efforts on the part of the expert and the knowledge engineer to incorporate the mathematical content of the schemes into the expert system. This places an undesirable constraint on the expert in the knowledge elicitation process. In using a simple scheme, knowing the shortcomings involved makes it possible to avoid the pitfalls and build a robust prototype system. A simple implementation of certainty factor based reasoning adopted in DEKBASE is presented below.

Consider a simple rule shown below. The rule can be considered to be a black box receiving an input (antecedents) and outputs some actions (consequents).

```
RULE    example 1 for CF
IF      A        AND     B      AND    C
THEN    D        AND     E
```

Assume that A, B and C are true with confidences of 90, 80 and 85, respectively. (Here confidence factors are used such that they can take values between 0 and 100.) What are the confidences of D and E? It is more appropriate to consider all conjunctions to be equal as in the case of links in a chain. The chain is only as strong as the weakest link. Therefore, the confidence of B governs the overall confidence of the input. The confidence of D and E are therefore set to a value of 80. Now consider another rule.

```
RULE    example 2 for CF
IF      A       OR       B      AND    C
THEN    D       AND      E
```

Here the only difference is that a disjunction is introduced in the form of OR. The disjunction A or B evaluates to true with a confidence value equal to the confidence value of the antecedent with the highest individual confidence in the disjunction. This is logical because it is necessary that any one antecedent needs to be true and the inference process aims to establish facts with the greatest possible confidence. Therefore in the above rule, the overall input confidence is taken as the minimum of 90 and 85. The value 90 is an outcome of the consideration that it is the maximum of the values 90 and 80. D and E are therefore assigned a confidence value of 85. Now let us see what happens if confidence values are assigned to consequents in the rule. Consider the following rule:

```
RULE   example 3 for CF
IF     A      OR      B     AND   C
THEN   D CF 90              AND   E CF 80
```

In the above rule, when the conditions in the antecedent part are satisfied, the deduction that D is true can be made with a confidence of 90 and E with a confidence of 80. The additional uncertainty in the knowledge should now be combined with the uncertainty of the facts, i.e., A, B and C. When confidence values are specified, confidence of the output is attenuated by the CF values after the overall confidence of the input is evaluated. In the above example, the overall input confidence is 85. D is then assigned a confidence of 76.5 (0.85 × 90) and E is assigned a confidence value of 68 (0.85 × 80). Now consider the following rule, which is just a restatement of the previous rule, but the order in which the first two conditions appear is interchanged.

```
RULE   example 4 for CF
IF     B      OR      A     AND   C
THEN   D CF 90              AND   E CF 80
```

If all antecedents in a disjunction are not considered, then A would not be considered at all and we would establish D and E with confidence values of 72 and 64, which are quite different from the previous case. The essential knowledge is the same. It is for the reason of consistent handling of uncertainty that rule interpretation is different when CONFIDENCE mode is toggled.

The way a rule is interpreted by the inference engine depends on the status of the confidence mode. In fact, the more important aspect is the manner in which the inference engine fires the rules in a rule base. The issue of rule triggering in the chaining process and conflict resolution aspects are presented with inexact reasoning both disabled and enabled. Consider a simple rule base having five rules.

```
RULE R1       IF    B
              THEN  C CF 80
              AND   F CF 90

RULE R2       IF    A
              THEN  C CF 90
              AND   F CF 80

RULE R3       IF    P
              THEN  D

RULE R4       IF    Q
              AND   R
              THEN  D

RULE R5       IF    C
              AND   D
              THEN  E
```

Assume that the goal is E and that A, B, P, Q and R are true with a confidence value of 100. First consider the case when inexact reasoning is disabled and the chaining mode is backward. The chaining process will be as shown below.

Attempt R5.	C is required
Attempt R2.	C is established with a confidence of 100
Attempt R5.	D is required
Attempt R3.	D is established with a confidence of 100
Attempt R5.	E is established with a confidence of 100

The following can be noted in the process of inference. There are two rules, which will establish C. Instead of selecting the first one (R1), the inference mechanism selected R2. This is because the conflict resolution strategy attempts establishing a fact in the decreasing order of CF values corresponding to the consequent establishing the fact in the respective rules. Had the goal been F instead of E, then R1 would have been attempted in place of R2. Also, when a rule establishes a fact, the other rules establishing the rule are not tried, implying that as R2 establishes C, R1 will not be attempted. Since inexact reasoning is disabled, a confidence of 100 is assigned to all the facts established.

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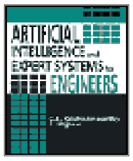

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The chaining process will be different, when inexact reasoning is enabled. Assume that A, B, P, Q and R are TRUE with confidence levels 85, 80, 75, 90 and 80, respectively. The chaining process is as shown below.

Attempt R5.	C is required
Attempt R2.	C is established with a confidence of 76
Attempt R1.	C is NOT reestablished because confidence is 64
Attempt R5.	D is required
Attempt R3.	D is established with a confidence of 75
Attempt R4.	D is reestablished with a higher confidence of 80
Attempt R5.	E is established with a confidence of 76

A comparison of the two chaining processes shows many differences. First, all the rules trying to establish a fact are attempted. If a rule establishes a fact with a higher confidence than the existing value, it is triggered. Otherwise the rule is ignored. This criterion is applied to all consequents in a rule independently. To understand this concept better, consider the following two rules, in which it is required to establish a fact X.

```
RULE   X1
IF     A
THEN   X CF 80
AND    Y CF 95

RULE   X2
IF     B
THEN   X CF 90
AND    Y CF 90
```

IF A and B are TRUE with confidence values of 100, then rule X2 establishes X and Y with a confidence of 90. When rule X1 is attempted, X can be established only with a confidence of 80 and so the rule is not triggered as far as X is concerned, but Y will be reestablished with a new confidence of 95.

One difficulty in the use of confidence levels as explained above is that, when confidence values are propagated over several levels, they tend to diminish rapidly. Some type of normalisation of confidence levels at every level can overcome this difficulty, but no reliable mechanism is available for such normalisation. Formalisation of uncertainty in knowledge is so difficult and involved that both the knowledge engineer and the expert will find it extremely difficult to quantify the qualitative nature of the uncertainty even to the level of confidence factors. Then one can imagine the efforts required to use highly mathematical theories for representation of uncertain knowledge and use them for inexact reasoning.

Expert System Development Shell

So far an overview of KBES technology is presented with detailed descriptions on knowledge representation and inference mechanisms with illustrative examples. To develop an expert system, one has to use either specialised languages or expert system development shells. An expert system development shell is more convenient to use since it provides an environment for the knowledge engineer or the developer to code and implement the knowledge without much difficulty. It also provides different knowledge representation schemes and inference mechanisms so that the developer can concentrate more on elicitation and organisation of knowledge and its implementation as a knowledge base, rather than going into the details of data structuring and coding the algorithms for inference processes. A brief review of the requirements of an expert system development tool is presented below.

Selection of a KBES development tool appropriate to the application area is an important step in the development of KBES. A number of criteria have been identified based on which a tool can be evaluated regarding its suitability for the development of a KBES in a particular domain. The important criteria are

Knowledge Representation: The tool should have enough expressive power for representing engineering concepts. The combination of scientific knowledge, that is often exact and complete, and heuristic information, which is based on empirical observations, is a critical issue in the development of a KBES. Ideally a combination of rules following the IF-THEN construct to represent the procedural knowledge and objects or frames to represent declarative knowledge can provide a powerful environment for development of a KBES in engineering disciplines. The combination should be such that the rules and frames should be able to interact with each other during the problem solving.

Inference Mechanism: The tool should have different inference mechanisms, such as backward chaining, forward chaining and hybrid chaining, so that a developer can select an appropriate one depending on the nature of the knowledge and the problem-solving strategy. It should also have mechanisms for implementing different types of inferences in a frame base environment. One such technique is use of different types of demons in frames. The knowledge representation and inference mechanism together should provide techniques to develop process models such as blackboard architecture with non-monotonic reasoning and other models which use components such as engineering design synthesis, design critiquing etc.

Developer Interface: A good developer interface should provide the expert system developer with tools such as a knowledge base editor, a knowledge debugging environment with a trace through the line of reasoning, facilities to examine context and modify values etc.

User Interface: Once the KBES has been implemented, its usability depends largely on the end user interface. The user interface should enable the user to interact efficiently with the KBES and should include menu systems, an interactive graphics facility and explanation facilities to make the system user friendly.

Programming Language Considerations: In addition to the structure and paradigms supported by a tool, the language in which the tool is written is of major importance. The language plays a major role in the compatibility and portability of the KBES. Similar considerations relate to the tool having language hooks for accessing other programs or database hooks for accessing information stored in popular databases. The KBES must also be able to call functions or programs written in other languages.

Hardware: The computers supported by the various tools are primarily a function of the language and operating system in which they are written, and the memory, processing and graphics display capabilities of individual computers. Software tools that require special purpose hardware are to be selected only if the KBES that is to be implemented is to be made available only in such systems.

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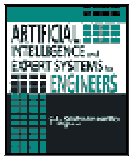

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Cost: The cost of the tool is a very important criterion. The cost of the tools used for implementing a KBES will reflect on the price of the product and in turn on the market for the KBES.

Other criteria for evaluating a development tool include ability of the tool to handle complex arithmetic, extensibility of the tool by way of incorporating new problem-solving and knowledge representation strategies that may evolve over a period of time and the degree of support offered by the vendors.

A number of KBES development tools are available now with different capabilities, which offer tools for developing expert systems in engineering. A few of them are OPS5 and OPS83, INSIGHT, Level5 Object, Prolog, VP-Expert, Teknowledge, Personal Consultant Plus, GEPSE, KEE, ART and KnowledgeCraft. Out of these OPS5, OPS83 and Prolog are more of a programming language type and others are specialised development tools. Important features of a few of the tools are presented below so that the readers can have a comparison.

OPS5 is a general purpose production system language for rule-based programming. Its main advantage is its stability and efficiency as has been demonstrated by its use in the development of a number of prototype systems, including R1 and XSEL. Though OPS5 provides a compound data type to define objects, its expressive power in representing declarative knowledge is inferior to that of the frame-based knowledge representation scheme. While the OPS5 inference engine is a forward chaining engine, the programmer can write rules to effect his own control strategies. External function and procedure calls in other languages are supported by some implementations of OPS5. The main disadvantages of OPS5 are its lack of a well-developed user interface and special editing and explanation facilities, and the lack of a formal method to represent structured objects.

OPS83 is an improvement on OPS5, which enables programmers to write very efficient and compact production system code. The data-typing features and user-defined functions and procedures of OPS83 resemble those in modern procedural languages. OPS83 is a hybrid programming tool in that it allows for multiple knowledge representation and inference schemes.

INSIGHT is a PC-based development environment for rule-based expert systems. INSIGHT uses a compiler for knowledge bases. This not only allows large knowledge bases to run in systems with less memory, but also makes knowledge bases run faster than interpretative systems such as Prolog. It provides a Production Rule Language (PRL) for development of knowledge bases. It has a number of facilities such as direct interfacing with databases, activation of programs written in other languages, use of confidence factors and inexact reasoning, a function key-driven environment and user-friendly interface. Level5 Object is also from the same company, which provides frame-based knowledge representation and a Windows-based environment for KBES development.

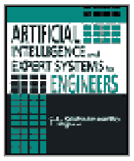
GEPSE is an environment for developing KBES for engineering problems. The key features of GEPSE are an Object Network Language (ONL) that simplifies construction of objects and rule bases, function libraries, functions for developing a user interface and a facility for meta-level control. The graphics functions supported by GEPSE provide facility to develop user interfaces for applications.

Prolog is an example of languages that are based on predicate logic, known as logic programming languages. Traditionally, computation in Prolog is viewed as a refutation of a goal using the rule of inference called resolution. However, Prolog can also be viewed as a backward chaining rule-based language with very specific information on what to do next. It has been widely used in Europe and Japan for implementing a wide variety of expert systems.

KEE is a widely used programming environment for implementing large and sophisticated KBES. KEE provides both rule base and frame base for knowledge representation schemes. It allows hierarchical modelling of objects with facilities for inheritance of hierarchies with defaults and demon procedures attached with slots. It has an open architecture with facility for user-defined inference methods, a truth maintenance system, logical operators, integration with C, accessing databases and LISP programs. KEE has been used for applications in diagnosis, monitoring, real-time process control, planning, design and simulation.

ART is a versatile tool incorporating a sophisticated workbench for use with advanced AI machines. ART’s strong point is viewpoints, a technique that allows hypothetical non-monotonic reasoning in which multiple solutions are carried along in parallel until constraints are violated or better solutions are found. At such points, inappropriate solutions are discarded. It provides graphical interfaces for browsing both its viewpoint and schema networks. ART has a flexible graphic workbench through which graphics interfaces and simulations can be created. It is particularly suitable for planning, scheduling, simulation and design applications. Both ART and KEE are expensive compared to the other tools.

The salient features of a KBES development environment provided by the expert system development shell of DEKBASE (Development Environment for Knowledge-Based Systems in Engineering) is presented in Appendix I.



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DEKBASE

The motivation behind the development of DEKBASE is the objective of developing prototype expert systems in engineering domains. Existing tools do not meet with all the requirements. Moreover, large prototypes are rather rare in engineering domains, and it was felt through a study of the problems arising during the prototype development process, the features required to address these problems could be devised and incorporated into the shell. Such an approach would result in identifying the architecture of a general purpose expert system shell for developing real-life prototypes in engineering, as also providing such a shell for realising the prototypes. The features of DEKBASE are described with an objective of enabling a beginner to understand how to use it to develop prototype expert systems [16,17]. Emphasis is placed on the different aspects of expert systems development, so that the readers can design and develop knowledge-based expert systems for problems such as diagnosis, classification, planning, monitoring and design in different domains of engineering. DEKBASE also provides interface to other knowledge-based systems development modules such as GENSYNT (module for design synthesis), GENCRIT (module for design criticism) and CASETOOL (module for case-based reasoning), which are explained in subsequent chapters of the book.

A typical example with three rule bases is presented in the section on knowledge representation, and the way the knowledge is used for inference is described in the section on inference techniques. Two more examples of the use of rule bases for two different types of problems are presented here. First is a system for selection of bearings having 16 rules. The second problem is a relatively large problem for planning, analysis and design of steel industrial structures.

Example 1: Selection of Bearings

This problem is a relatively trivial one and typically illustrates a simple classification task. The knowledge net for the problem is presented in Figure 3.14. The knowledge net has 16 nodes representing 6 goal states, 7 initial states and 3 intermediate states. The knowledge coded in the rule base is typically adaptable for backward chaining. The rule base representing the knowledge in the knowledge net is given below.

```
TITLE   Expert System for Bearing Selection
BOOLEAN  silent running important,
shaft misalignment with housing, moderate axial loading,
heavy radial loading, moderate radial loading,
light radial loading, silent normal environment,
noisy normal environment, silent clean environment,
silent running needed, high speed shaft, medium speed shaft,
low speed shaft and housing, bearing is selected
STRING  loading type, loading class,
dominant load component, running speed, rotating part

GOAL    bearing is selected

RULE    moderate axial loading #1
IF      loading class IS moderate
AND     dominant load component IS axial
THEN    moderate axial loading

RULE    heavy radial loading #2
IF      loading class IS heavy
AND     dominant load component IS radial
THEN    heavy radial loading

RULE    moderate radial loading #3
IF      loading class IS moderate
AND     dominant load component IS radial
THEN    moderate radial loading

RULE    light axial loading #4
IF      loading class IS light
AND     dominant load component IS radial
THEN    light radial loading

RULE    silent normal #5
IF      silent running needed
AND     working environment IS normal
THEN    silent normal environment

RULE    noisy normal #6
IF NOT  silent running needed
AND     working environment IS normal
THEN    noisy normal environment

RULE    silent clean #7
IF      silent running needed
AND     working environment IS clean
THEN    silent clean environment

RULE    high shaft #8
IF      running speed IS high
AND     rotating part IS shaft
THEN    high speed shaft

RULE    medium shaft #9
IF      running speed IS medium
AND     rotating part IS shaft
THEN    medium speed shaft

RULE    low shaft and housing #10
IF      running speed IS low
AND     rotating part IS shaft and housing
THEN    low speed shaft and housing

RULE    bearing type_1 #11
```

```
IF      loading type IS radial and axial
AND     of shaft misalignment with housing
AND     moderate axial loading
AND     high speed shaft
AND     silent normal environment
THEN    bearing is selected
AND     DISPLAY type_1

RULE    bearing type_2 #12
IF      loading type IS radial and axial
AND NOT shaft misalignment with housing
AND     heavy radial loading
AND     high speed shaft
AND     noisy normal environment
THEN    bearing is selected
AND     DISPLAY type_2

RULE    bearing type_3 #13
IF      loading type IS radial
AND NOT shaft misalignment with housing
AND     light radial loading
AND     medium speed shaft
AND     silent clean environment
THEN    bearing is selected     AND   DISPLAY type_3

RULE    bearing type_4 #14
IF      loading type IS radial and axial
AND     shaft misalignment with housing
AND     moderate radial loading
AND     medium speed shaft
AND     noisy normal environment
THEN    bearing is selected     AND   DISPLAY type_4

RULE    bearing type_5 #15
IF      loading type IS radial and axial
AND     shaft misalignment with housing
AND     heavy radial loading
AND     low speed shaft and housing
AND     noisy normal environment
THEN    bearing is selected     AND   DISPLAY type_5

RULE    bearing type_6 #16
IF      loading type IS radial and axial
AND NOT shaft misalignment with housing
AND     moderate radial loading
AND     high speed shaft
AND     noisy normal environment
THEN    bearing is selected     AND   DISPLAY type_6
END
```

The rule base is coded following the syntax of DEKBASE, which is described in Appendix I. The DISPLAY tags mentioned in the rule base (type_1 to type_6) are not given here. The complete knowledge base is given in the diskette provided with the book.

Figure 3.14 Knowledge net for bearing selection problem

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Example 2: Planning and Design of Steel Industrial Structures

Use of KBES technology is illustrated using a problem of planning and design of steel industrial structures [18]. The aim of this example is to illustrate how a complex engineering design problem can be planned and implemented using a knowledge-based approach.

A very brief description of the industrial building design process is given to place the ensuing illustration in proper perspective. The perspective view of a typical industrial building is shown in Fig. 3.15. The building essentially consists of a roof supported on purlins which rest on trusses. The trusses in turn rest on columns that finally carry the loads down to the foundation located below the ground.

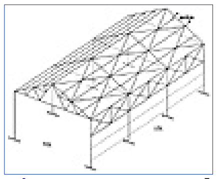

Figure 3.15 Steel industrial building

The first task in the design process is to determine the shape of the building, the sizes of the various segments and the height from the floor to the ceiling at various points in the building. These have to be decided based on the kind of equipment to be housed, the direction of process flow etc.

Following the spatial planning, the columns have to be located. Constraints may be placed on column locations because of the need to provide unobstructed space to house large machines. The location of columns is arrived at by generating Column Lines (*CLs*). Column lines are potential lines along which columns can be located. For arriving at the actual column locations, CLs are generated in the two orthogonal directions (these are called Longitudinal Column Lines, LCLs, and Transverse Column Lines, TCLs). Columns are then placed at the intersection of these lines.

Once the location of columns is decided, the type of trusses to be used is determined. The truss type depends on the spacing between columns. Once the trusses for the building have been chosen, a detailed analysis is carried out to determine the response of the structure to loads. The various individual structural components are then configured to resist the design forces and the details of how the members are to be connected at joints is also done. Finally the construction drawings are prepared.

This is a complex problem involving knowledge-based inference, procedural programs, access to databases and communication of information between knowledge modules and program modules through frames. The knowledge base consists of six rule bases, which are fairly large, and a number of frames, C functions and external programs. Only a few representative rules are presented here, which will help the readers understand how a complex problem is reduced to a sequence of smaller problems of knowledge and data processing. Figure 3.16 shows the problem reduction and the organisation of different modules. A brief description of the rule bases are given below. (An extension .RL is used to indicate rule bases and .EXE is used to indicate external executable programs).

INIT.RL This rule base initialises the session. Since every session starts with user specification of a problem, the external programs for obtaining the problem data, planning etc. are invoked. After completing the inference, it loads another rule base PLAN.RL.

```
TITLE   Initialising Session
RULE    for obtaining input
IF NOT  input obtained
THEN    RUN input          # run external pgm
AND     FLOAD_FBASE layout.fbs
AND     FSELECT_FBASE layout.fbs
AND     input obtained
AND     LOAD plan          #loads plan.rl
END
```

PLAN.RL This rule base generates column lines in both longitudinal and transverse directions for each rectangular portion. The values along with the data obtained from the program input.exe are required for configuring the components of the industrial building. A procedural program plan.exe is called from this rule base to carry out the planning and detailed configuration. The rule base CONFIG.RL that does the job of configuring is called from this rule base. Planning and configuration have to be done for each segment separately, implying that inference using this rule base has to be carried out in an iterative manner. The iteration is forced when rule 8 is fired, which has an action RESTART. It may be noted that at the beginning of each iteration, the variables which get modified during the inference are initialised. This is achieved using a qualifier CLEAR in the declarations of those variables. The program plan.exe modifies the frame base *layout.fbs*, which is loaded before loading the next rule base CONFIG.RL.

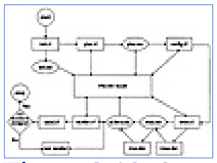

Figure 3.16 Organisation of knowledge modules for industrial building design system

```
TITLE Assigning LCL Spacings to Segments
/* only typical variable declarations are given */

BOOLEAN    lcl spacing assigned,
           all segments have been considered,
           current segment is known,
           recorded values in frame
INTEGER    segment number
NUMERIC    minimum lcl spacing,
           maximum lcl spacing,
           clear height in segment
STRING     current segment, class name

CLEAR lcl spacing assigned
CLEAR clear height in segment
CLEAR all segments have been considered
CLEAR current segment is known
CLEAR minimum lcl spacing
CLEAR maximum lcl spacing
CLEAR recorded values in frame
#CLEAR flag used for iterative execution of the rule base

SET   segment number = 1
SET   class name IS segment

GOAL  all segments have been considered

RULE  one
IF    clear height in segment <= 6.0
THEN  minimum lcl spacing = 9.0
AND   maximum lcl spacing = 18.0
AND   lcl spacing assigned

RULE  two
IF    clear height in segment > 6.0
AND   clear height in segment <= 9.0
THEN  minimum lcl spacing 12.0
AND   maximum lcl spacing 24.0
AND   lcl spacing assigned

RULE  three
IF    clear height in segment > 9.0
AND   clear height in segment <= 12.0
THEN  minimum lcl spacing = 15.0
AND   maximum lcl spacing = 30.0
AND   lcl spacing assigned

RULE  four
IF    clear height in segment > 12.0
THEN  minimum lcl spacing = 30.0
AND   maximum lcl spacing = 60.0
AND   lcl spacing assigned

RULE  five
IF    current segment is known
THEN  clear height in segment =
               FRAME(currentsegment,clear_ht,1)

RULE  six
IF    segment number <= FRAME(bldg,nsegs,1)
THEN  current segment IS
               getinstanceName(class name, segment number)
AND   current segment is known

RULE  seven
IF    lcl spacing assigned
THEN  FADD_ATTR current segment, FDOUBLE,
            min_lcl_spacing, max_lcl_spacing
AND   FINSERT_VAL current segment, min_lcl_spacing,1,
            minimum lcl spacing
AND   FINSERT_VAL current segment, max_lcl_spacing,1,
            maximum lcl spacing
AND   recorded values in frame

RULE  eight
IF    recorded values in frame
AND   segment number >= FRAME(bldg,nsegs,1)
THEN  all segments have been considered
AND   FSAVE_FBASE layout.fbs
AND    FDEL_FBASE layout.fbs
AND    RUN plan             # do the planning
AND    FLOAD_FBASE layout.fbs
AND    FSELECT_FBASE layout.fbs
AND    LOAD config          # loads config.rl
ELSE   segment number = segment number + 1
                                    # goto next segment
AND    RESTART              # restart for next segment
END
```

CONFIG.RL This rule base assigns a framing type for each aisle and arrives at the shape of the truss to be provided. Only two types of trusses are considered for illustration. It may be noted that a C function *getInstNo ()* is called in a rule to obtain the current aisle number. Another rule base TRUSS.RL is loaded after completing all the tasks of configuration. Only typical rules are given.

```
TITLE   assign framing type in each aisle
GOAL    all aisles have been considered
RULE    for current aisle
IF      current aisle is known
THEN    clear height in aisle FRAME(current isle,clear_ht,1)
AND     floor height in aisle FRAME(current isle,floor_ht,1)
AND     eave height of truss = clear height in aisle +
                floor height in aisle
AND     flow direction IS FRAME (current aisle,flow_dir,1)
AND     truss spacing=FRAME(current aisle, truss_spacing,1)
AND     aisle x1 = FRAME (current aisle,aisle_area_x1,1)
AND     aisle y1 = FRAME (current aisle, aisle_area_y1,1)
AND     aisle x2 = FRAME (current aisle, aisle_area_x2,1)
AND     aisle y2 = FRAME (current aisle, aisle_area_y2,1)

RULE    for span of truss
IF      flow direction IS EAST_WEST
THEN    span of truss = aisle y2 - aisle y1
ELSE    span of truss = aisle x2 - aisle x1

RULE    getting instance
IF      aisle number <= FRAME (bldg,naisles,1)
THEN    current aisle IS getInstNo (class name, aisle number)
AND     current aisle is known

RULE    storing values
IF      truss type assigned
THEN    FADD_ATTR current aisle, FSTRING, truss_shape
AND     FINSERT_VAL current aisle, truss_shape,
              shape of truss
AND     recorded values in frame

RULE    for truss type 1
IF      span of truss <= 8.0
THEN    shape of truss IS North_Light_Type
AND     rise of truss = span of truss /5   # overridable
```

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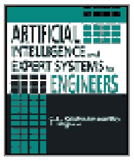

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… Other rules for configuring are omitted…

```
     RULE    for loading rule base TRUSS
     IF      all aisles have been considered
     THEN    run TRUSS
     AND     configuration completed
     END
```

TRUSS.RL This rule base first obtains truss details by loading the frame base created by the preceding rule base and arrives at parameters such as number of panels for the truss, cross section of purlins, viz., angle or channel. The section properties are obtained from a database, using a database query DBMS from the rule base. It also computes loads on the truss and calls a C function *ConfigureTruss()*, which creates a data file for analysis. At the end, the rule base loads an executable file TRUSS.EXE to carry out analysis and store results in an output file for further processing. Only typical rules are presented for each process.

```
     TITLE   Truss Configuration and Design
     GOAL    building details obtained, truss details obtained,
             purlin designation, configuration over,analysis is over

     RULE    to read details from frame #1
     IF      FEXIST_FRAME bldg
     THEN    latitude of site = FRAME(bldg,latitude,1)
     AND     terrain type IS FRAME(bldg,terrain,1)
     AND     basic wind speed = FRAME(bldg,wind_speed,1)
     AND     design life of building = FRAME(bldg,design_life,1)
     AND     process type IS FRAME (bldg,process,1)
     AND     natural lighting IS FRAME(bldg,nat_lighting,1)
     AND     permeability of bldg IS FRAME(bldg, permeability, 1)
     AND     length of building = FRAME(bldg,length,1)
     AND     width of building = FRAME(bldg,width,1)
```

```
 AND     orientation of building IS FRAME(bldg,orientation,1)
 AND     building details obtained
 ELSE    DISPLAY err1
 AND     STOP

 RULE    to read truss details from frame #2
 IF      FEXIST_FRAME truss_details
 THEN    span of truss = FRAME(truss_details,span,1)
 AND     rise of truss = FRAME(truss_details,rise,1)
 AND     direction of truss IS FRAME(truss_details,truss_dir,1)
 AND     roof material IS FRAME(truss_details,roof_matl,1)
 AND     eaves ht of truss = FRAME(truss_details,eaveht,1)
 AND     clear height of truss =FRAME(truss_details,clearht,1)
 AND     shape of truss IS FRAME(truss_details,shape,1)
 AND     truss details obtained
 ELSE    DISPLAY err2
 AND     STOP

# rules to configure the truss
 RULE NL 1
 IF      span of truss <= 3.9
 AND     shape of truss IS North_Light_Type
 THEN    number of panels = 3

 RULE NL 4
 IF      span of truss <= 8.0
 AND     span of truss > 6.6
 AND     shape of truss IS North_Light_Type
 THEN    number of panels = 6

 RULE A 1
 IF      span of truss > 8.0
 AND     span of truss <= 10.5
 AND     shape of truss IS A_Type
 THEN    number of panels = 4

 RULE A 4
 IF      span of truss > 21.0
 AND     span of truss <= 26.5
 AND     shape of truss IS A_Type
 THEN    number of panels = 10

# Rules for loads and purlin design
 RULE    to calculate slope of NL roofs
 IF      truss details obtained
 AND     shape of truss IS North_Light_Type
 THEN    slope of roof = (180/3.1416) * atan(rise of truss /
         span of truss)

 RULE    LL 1 # Rules for Live Load
 IF      slope of roof <= 10
 AND     access to roof IS provided
 THEN    live load per m2 = 150

 RULE    LL 3
 IF      slope of roof > 10
 THEN    live load per m2 = 75 - 2*(slope of roof - 10)

# Rules for dead load
 RULE    DL of truss #DL1
 IF      truss details obtained
```

```
THEN    dead weight of truss per m2 = span of truss/3 + 5

RULE    DL of roofing 1 #DL2
IF      roofing material IS Gauze 24 GI sheeting
THEN    weight of roof mtrl per m2 = 7.34

RULE    DL of roofing 2 #DL3
IF      roofing material IS Gauze 22 GI sheeting
THEN    weight of roof matrl per m2 = 9.30

RULE    DL of roofing 3 #DL4
IF      roofing material IS Gauze 20 GI sheeting
THEN    weight of roof matr per m2 = 11.27

# Rules for wind load
RULE    for design wind spd and wind pr
IF      building details obtained
THEN    design wind speed = risk coeft * terrain factor
        * basic wind speed
AND     design wind pressure = 0.06 * design wind speed
        * design wind speed

RULE    for risk coefficient 1
IF      class of structure IS temporary shed or building
OR      design life of building <= 5
THEN    risk coefficient = 0.83

RULE    for risk coefficient 3
IF      class of structure IS ordinary industrial structure
OR      class of structure IS general building
OR      class of structure IS office building
OR      class of structure IS commercial structure
THEN    risk coefficient = 1.0

RULE    for int pressure coeff 1
IF      permeability of building IS Low
THEN    internal pressure coefficient = 0.2

RULE    for int pressure coeff 3
IF      permeability of building IS High
THEN    internal pressure coefficient = 0.7

RULE    for ht_wd ratio
IF      NOT height width ratio IS_DEFINED
THEN    height width ratio = eave height of truss /
        max dimension of building

RULE    for purlin spacing 1
IF      shape of truss IS North_Light_Type
THEN    rafter length = sqrt (span of truss * span of truss +
        rise of truss * rise of truss)
AND     purlin spacing = rafter length / number of panels

RULE    for purlin spacing 2
IF      shape of truss IS A_Type
THEN    rafter length = sqrt (0.25 * span of truss *
        span of truss + rise of truss * rise of truss)
AND     purlin spacing = rafter length / number of panels

RULE    for purlin section #PD3
IF      spacing of trusses > 8.0
```

```
THEN    purlin section IS trussed section
ELSE    purlin section IS rolled section

RULE    to decide purlin section 1
IF      purlin section IS rolled section
AND     spacing of trusses <= 5.0
THEN    actual purlin section IS Angle_Section

RULE    to decide purlin section 2
IF      purlin section IS rolled section
AND     spacing of trusses > 5.0
THEN    actual purlin section IS Channel_Section

RULE    typical for DL of purlins 1
IF      NOT self weight of purlins IS_DEFINED
AND     spacing of trusses <= 5.0
THEN    self weight of purlins = 10 # kg/m
AND     self weight of purlins is assumed

RULE    for DL on purlins #PD12
IF      self weight of purlins is assumed
THEN    sheet wt on purlin per m =
        weight of roofing material per m2 * purlin spacing
AND     DL on purlin per m = sheet wt on purlin per m +
        self weight of purlins
AND     LL on purlin per m = live load per m2 *
        cos ((3.1416/180) * slope of roof)*purlin spacing
AND     vert load on purlin is known

RULE    for WL on purlins
IF      vert load on purlin is known
THEN    WL on purlin per m =
        ABS (external pressure coefficient -
        internal pressure coefficient) *
        design wind pressure*purlin spacing
AND     wind load on purlin is known

RULE    for loads on purlins #PL1
IF      vert load on purlin is known
AND     wind load on purlin is known
THEN    loads on purlin are known

RULE    for load combination on purlins
IF      1.5 * (DL on purlin per m + LL on purlin per m) >
        ABS (DL on purlin per m - WL on purlin per m)
THEN    design loading combination IS DL_LL
AND     load determination is over
ELSE    design loading combination IS DL_WL
AND     load determination is over

RULE    for design moments in purlins
IF      load determination is over
THEN    Mx_DL = DL on purlin per m *
        cos((3.1416/180)*slope of roof) *
        purlin span xx*purlin span xx / 10.0
AND     My_DL = DL on purlin per m *
        sin((3.1416/180)*slope of roof) *
        purlin span yy*purlin span yy / 10.0
AND     Mx_LL = LL on purlin per m *
        cos((3.1416/180)*slope of roof) *
        purlin span xx*purlin span xx / 9.0
```

```
AND     My_LL = LL on purlin per m *
        sin((3.1416/180)*slope of roof) *
        purlin span yy*purlin span yy / 9.0

RULE    for design moment
IF      design loading combination IS DL_LL
THEN    Mx = Mx_DL + Mx_LL
AND     My = My_DL + My_LL
AND     design moments are known
ELSE    Mx = ABS(Mx_DL - Mx_WL) AND My = My_DL
AND     design moments are known

RULE    to get angle purlin designation
IF      design moments are known
AND     actual purlin section IS Angle_Section
THEN    Zx reqd = Mx * 100 / permissible stress in bending
AND     DBMS(angle; Zxx > Zx reqd;desig,wt)
AND     purlin designation IS desig
AND     purlin is designed

RULE    to obtain channel purlin section
IF      design moments are known
AND     actual purlin section IS Channel_Section
THEN    purlin designation IS getChlSection (Mx*100,My*100,
        permissible  stress in bending)
AND     DBMS(channel;desig IS purlin designation;wt)
AND     purlin is designed

/* rules for setting up the design loads on
  truss and call truss.exe for analysis */

RULE    for determining truss point loads
IF      DL per panel is known
AND     LL per panel is known
AND     WL per panel is known
AND     configuration over
THEN    flag2 = setupAnalysis (DL per panel,LL per panel,
        WL per panel)
AND     RUN truss.exe
AND     analysis is over
AND     LOAD members
END
```

MEMBERS.RL This rule base carries out computation of member design forces after extracting required information from the relevant frames. This rule base is executed in an iterative manner. In every iteration, another rule base AXIAL.RL is loaded.

```
TITLE   designing the truss members
GOAL    details available,
all     members have been designed

RULE    for entry check
IF      NOT FEXIST_FRAME truss_configuration
THEN    DISPLAY err1
AND     STOP
ELSE    details available
AND     member number = 1

RULE    for getting input
IF      current member is known
THEN    DL force = FRAME(current member,DLf,1)
```

```
AND     LL force = FRAME(current member,LLf,1)
AND     WL force = FRAME(current member,WLf,1)
AND     length of member =FRAME(current ember,length,1)

AND     member class IS FRAME(current member,type,1)
AND     DL_LL force = DL force + LL force
AND     DL_WL force = DL force + WL force

RULE    for determining design forces
IF      DL_LL force < 0.0
THEN    comp force in member = DL_LL force
AND     tension force in member = DL_WL force
ELSE    comp force in member = DL_WL force
AND     tension force in member = DL_LL force

RULE    for current instance
IF      member number <=
        FRAME(truss_configuration,nmembs,1)
THEN    current member IS getInstanceName
        (class name, member number)
AND     current member is known

RULE    recording values in frame
IF      current member is designed
THEN    FADD_ATTR current member, FSTRING, desig
AND     FINSERT_VAL current member,
        desig,1,axial member designation
AND     recorded values in frame
AND     DISPLAY d11
AND     UNDEFINE current member is designed
AND     UNDEFINE axial member designation

RULE    looping control
IF      recorded values in frame
AND     member number >=
        FRAME(truss_configuration,nmembs,1)
THEN    all members have been designed
AND     flag1 = setupTrussDrg(connection material code)
ELSE    member number = member number + 1
AND     RESTART

RULE    for section of member
IF      member class IS RAFTER
OR      member class IS MAIN_TIE
OR      member class IS MAIN_SLING
THEN    member section IS Double_Angle_Section
ELSE    member section IS Single_Angle_Section

RULE    for effective length 1
IF      member section IS Single_Angle_Section
THEN    effective length of mbr = 0.85 * length of member

RULE    for effective length 2
IF      member section IS Double_Angle_Section
THEN    effective length of mbr = 0.70 * length of member

RULE    for designing the current member
IF      axial member frame is created
THEN    FADD_ATTR axial_member_details,
        FDOUBLE, m_eff_length, m_length,
        m_comp,m_tension
```

```
AND     FADD_ATTR axial_member_details,
        FSTRING, m_section,m_con_matl,m_role
AND     FINSERT_VAL axial_member_details,
        m_length,1,length of member
AND     FINSERT_VAL axial_member_details,
        m_eff_length,1, effective length of member
AND     FINSERT_VAL axial_member_details,
        m_comp,1,comp force in member
AND     FINSERT_VAL axial_member_details,
        m_tension,1,tension force in member
AND     FADD_ATTR current member, FSTRING, section
AND     FINSERT_VAL current member,
        section,1,member section
AND     FINSERT_VAL axial_member_details,
        m_section,1,member section
AND     FINSERT_VAL axial_member_details,
        m_con_matl,1,connection material
AND     FINSERT_VAL axial_member_details,
        m_role,1,member class
AND     current member is designed
AND     DISPLAY d12 AND        LOAD axial
END
```

AXIAL.RL This rule base uses the frame axial member details having all the data for design. Information required for carrying out design is stored in the frame base, which is loaded when the rule base is loaded. This rule base is called for design of each axial member. All the results are stored in the frame base, which are later used by drawing programs. (Rule bases and functions required for preparation of detailed drawing are not presented here.) The design procedure itself is iterative. Depending on the section type desired, the inference process starts with the first available section. It computes the compression and tension capacities of the selected section and if found satisfactory, returns the control to the calling rule base, or else it explores the next section and restarts.

```
TITLE   design of truss member for axial load
GOAL    axial member details available,
        axial member designation

RULE    for entry check
IF      NOT FEXIST_FRAME axial_member_details
THEN    DISPLAY err1
AND     STOP
ELSE    axial member details available
AND     trial count = 0

RULE    for downloading info
IF      axial member details available
THEN    length = FRAME (axial_mbr_details,m_length,1)
AND     compression = FRAME (axial_mbr_details,
        m_comp,1) * -1.0
AND     tension = FRAME (axial_mbr_details, m_tension,1)
AND     section IS FRAME (axial_mbr_details, m_section,1)
AND     connection mtrl IS FRAME(axial_mbr_details,matl,1)

RULE    for checking eff_length
IF      NOT FEXIST_ATTR axial_mbr_details,m_eff_length
THEN    effective length = effective length factor * length
ELSE    effective length = FRAME
        (axial_mbr_details,m_eff_length,1)

RULE    for getting trial section 1
IF      NOT trial member IS_DEFINED
```

```
  THEN    trial member IS getTrialSection (section,trial count)

  RULE    for getting the properties from database 1
  IF      trial member obtained
  AND     section IS Single_Angle_Section
  OR      section IS Double_Angle_Section
  THEN    DBMS (angle;desig IS trial member;
          area, rxx, rvv,depth,width,tf)

  RULE    for checking comp 2
  IF      actual stress in comp <= allowable stress in comp
  AND     slenderness is ok THEN comp check ok
  ELSE    trial count = trial count + 1
  AND     RESTART

  RULE    for success
  IF      comp check ok AND tension check ok
  THEN    axial member designation IS trial member
  AND     current member is designed
  AND     DISPLAY figure AND LOAD members

/* rules for slender check and tension check are not included */
  END
```

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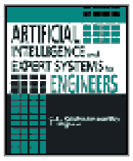

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This example illustrates how a complex problem requiring different types of computational models are decomposed into smaller problems and then solved using an appropriate problem-solving strategy. The example reported is part of a complete prototype developed for Planning, Analysis and Design and Steel Industrial Structures. Only modules required for planning, truss configuration and design of truss members are presented with typical rules. The objective of this presentation is to give the readers an idea on design and implementation of large knowledge-based systems. The concepts such as problem decomposition process, modular development of rule bases, communication between rule bases through frames, access of database query from rules, invoking procedural programs and functions from rules etc. are illustrated through the presentation of the example.

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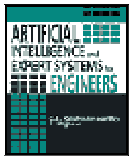

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Chapter 4
Engineering Design Synthesis

4.1 Introduction

The engineering design process consists of different, though not entirely distinct, stages such as the conceptual design phase, the preliminary design phase, analysis, design, detailing and drafting, and so on. Each of these in turn can be further divided into subtasks. The conceptual design phase wherein the designer investigates many potential alternatives and makes fundamental choices that have major impact on the downstream decisions is one of the important areas to be considered from the standpoint of automation. Creativity on the part of the designer is vital in obtaining desirable solutions. The problem of creativity is compounded by the fact that at this stage of the design, every parameter of design may correspond to a fairly large set of options. Deficient reasoning at this stage results in more iterations at later stages of the design process since the basic form of the solution is identified in this phase. An important characteristic feature of conceptual design is that typically several feasible design solutions are developed and evaluated.

It has been brought out in earlier publications that commonly used representation schemes in knowledge-based systems such as rules, frames etc., and control mechanisms such as forward chaining, backward chaining or hybrid chaining do not provide efficient strategies for building design process models for real-life applications [1–6]. In this chapter the generic nature of the approach to conceptual design is brought out as design synthesis. The use of design synthesis is shown to be efficient for dealing with specialised design subtasks such as proposing a set of feasible solutions and it provides a powerful methodology for building flexible knowledge-based systems [7–9]. A software tool, GENSYNT, for design synthesis is described [9]. The use of GENSYNT is illustrated through examples.

4.2 Synthesis

Design synthesis involves the generation of one or more design solutions consistent with the requirements defined during formulation of the design problem and any additional requirements identified during synthesis. During design synthesis the form of the solution is identified and arrived at. This phase of the design process is not well supported by computer-based tools unless the problem can be formulated in mathematical terms, in which case certain classes of synthesis problems can be formulated as an objective function and constraints and optimisation techniques can be used to solve them.

In general such formulations are always nonlinear and mathematical programming techniques are used to obtain optimal solution. In spite of research in this area for a long period of time, not much impact could be made on the application of these optimisation techniques to practical problems. The reasons include (a) mathematical programming techniques require complete definition of the problem, whereas in real-life situations even the number of design variables themselves cannot be fixed a priori as in the case of shape optimisation problems, and (b) many of the practical considerations, such as the availability of only a set of discrete sizes etc., cannot be handled so well in these techniques.

However in the last few years research and development in Genetic Algorithms (GA) show promise for application to design optimisation. It has been shown that GA-based methodologies can be developed which can take into account many of the practical considerations of design [10,11]. Since the synthesis process involves generation of a number of feasible solutions, process models can be developed using the GA-based approach with an additional advantage of obtaining an optimal solution.

The recent use of knowledge-based systems for synthesis design descriptions has shown promise and has formed the basis for various models that have been proposed for design synthesis. Several process models for synthesis have been proposed and reported in the literature [8,12]. The three broad approaches to design synthesis which can be used for engineering design are problem reduction, case-based reasoning and transformation.

Synthesis by problem reduction (problem decomposition-solution recomposition)

A design problem in engineering can be resolved into a set of smaller subproblems. Each subproblem in turn may consist of a further set of subproblems and so on until eventually terminating in making a functional or physical selection. Such a representation is termed as decomposition [7,8]. Decomposition continues until a subproblem can be managed without further decomposition. At this stage, the subproblem can be solved by simple selection amongst a set of possible values or by applying a simple method or procedure to resolve the problem. To apply the problem reduction approach, it is necessary to express the knowledge about the problem in a hierarchical manner. Usually this involves identification of physical objects comprising the solution and defining the hierarchy formed by them. Then, considering the interaction between subsystems and the constraints, solutions can be recomposed into coherent whole solutions. The details of domain decomposition and recomposition are illustrated through examples in the next section.

Synthesis by case-based reasoning

This approach requires past cases or examples of designs (solutions) and knowledge about how to transform a previous design (solution) so that it will satisfy the present requirements [13]. A case represents an instance of past design solutions. Cases can be episodic or can represent the result of abstraction and generalisation over several episodes. Successful use of the case-based approach needs efficient algorithms and knowledge representation schemes to retrieve relevant cases and transform a past case to suit the requirements of the present situation. A framework and software tool required for carrying out case-based reasoning is described in Chapter 6.

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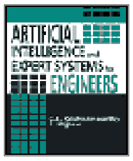

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Synthesis by transformation approach

Transformation, like case-based reasoning, adopts a holistic approach to design, but unlike case-based reasoning which uses specific episodes, it uses generalisations. In the transformation model, design knowledge is expressed as a set of transformational rules in which the left-hand side (LHS) of the rule is replaced by the right-hand side (RHS) of the rule. The most common application of the transformation model is manifested as grammars. The issues associated with using this model are representation of the design description, control in selection of an eligible transformational rule and termination of the application of rules [12].

4.3 Decomposition Model for Synthesis

The most ubiquitous of the synthesis models is the decomposition model [8]. It originates from the idea of dividing large complex problems into smaller less complex problems for ease of solution. In this model, the artifact to be designed is decomposed into a hierarchical network of systems and attributes. Each system is, in turn, decomposed into its subsystems and attributes until eventually terminating in a physical or functional selection. The leaf-level entity in the tree is called an attribute. All the other nodes in the hierarchical tree including the root node are referred to as systems. Also when referring to systems at two intermediate levels of abstraction (in the tree), the system in the lower level is referred to as a subsystem of its parent system. Thus the process of decomposition continues till every leaf node in the tree is an attribute and the value of the attribute has to be assigned or computed. The process of generating a solution consists of progressively building up the smaller components from the attribute level and using them to build up larger components and so on until the complete solution is obtained. This process of starting at the lowest level and proceeding up the tree assembling systems is called recomposition.

An important issue that arises with respect to decomposition knowledge is regarding what is decomposed. Decomposing a problem into subproblems can be viewed in two ways: (1) Decomposing a domain into various physical components that are used to construct the solution. Decomposing a building system into its various physical components like beams and columns is an example of this type of decomposition, (2) Decomposing it into various functions that must be provided for by the design solution. The same building system can also be decomposed into the subsystems on the basis of the functions that they are supposed to serve, viz., the various types of loads that they are supposed to resist. The first approach can be referred to as decomposition in terms of form while the latter is a function-centred approach to decomposition.

Since design knowledge comprises knowledge of both types (function and form), one approach to avoid the dilemma of decomposition based on function or form is to ignore the distinction and evolve a uniform representation for both function and form. In such an approach, every node in the decomposition hierarchy is termed as a *goal* and may in turn represent a *function* or *form*.

To understand decomposition and the alternate solutions generated as synthesis proceeds, consider a simple example of a system A as shown in Figure 4.1.

Consistent with the discussion presented earlier, every node in this decomposition (denoted in uppercase letters) is a *goal*. The decomposition tree has the form of an AND/OR graph. The system A (artifact) is decomposed into attributes A1 and A2, and system B, which thus becomes a subsystem of A. System B in turn is decomposed into its attributes B1 and B2. In synthesis terminology, A1, A2, B1 and B2 which are the leaf nodes of the decomposition tree are the attributes, and can take any one of the values, say, a1, a2, a3, a4; b1, b2, b3, b4, respectively.

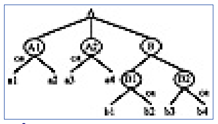

Figure 4.1 Decomposition of system A

The synthesis process builds up the solution by assigning values to the attributes at the lowest level in the hierarchical tree and combining them to form systems leading to the artifact. It is a depth-first search because it moves deeper into the hierarchy before completing a level.

There are sixteen possible solutions to the synthesis problem represented by the tree shown in Figure 4.1, i.e., sixteen different ways in which system A can be recomposed. These possible solutions are given in Table 1 and the sequence in which the solutions are generated follows the depth-first search.

Table 1 Sixteen Possible Solutions

S. No. 1
A.A1 = a1
A.A2 = a3
B.B1 = b1
B.B2 = b3
	S. No. 5
	A.A1 = a1
	A.A2 = a4
	B.B1 = b1
	B.B2 = b3
		S. No. 9
		A.A1 = a2
		A.A2 = a3
		B.B1 = b1
		B.B2 = b3
			S. No. 13
			A.A1 = a2
			A.A2 = a4
			B.B1 = b1
			B.B2 = b3

S. No. 2
A.A1 = a1
A.A2 = a3
B.B1 = b1
B.B2 = b4
	S. No. 6
	A.A1 = a1
	A.A2 = a4
	B.B1 = b1
	B.B2 = b4
		S. No. 10
		A.A1 = a2
		A.A2 = a3
		B.B1 = b1
		B.B2 = b4
			S. No. 14
			A.A1 = a2
			A.A2 = a4
			B.B1 = b1
			B.B2 = b4

S. No. 3
A.A1 = a1
A.A2 = a3
B.B1 = b2
B.B2 = b3
	S. No. 7
	A.A1 = a1
	A.A2 = a4
	B.B1 = b2
	B.B2 = b3
		S. No. 11
		A.A1 = a2
		A.A2 = a3
		B.B1 = b2
		B.B2 = b3
			S. No. 15
			A.A1 = a2
			A.A2 = a4
			B.B1 = b2
			B.B2 = b3

S. No. 4
A.A1 = a1
A.A2 = a3
B.B1 = b2
B.B2 = b4
	S. No. 8
	A.A1 = a1
	A.A2 = a4
	B.B1 = b2
	B.B2 = b4
		S. No. 12
		A.A1 = a2
		A.A2 = a3
		B.B1 = b2
		B.B2 = b4
			S. No. 16
			A.A1 = a2
			A.A2 = a4
			B.B1 = b2
			B.B2 = b4

Besides having knowledge of the system hierarchy, it is desirable to have knowledge to rule out an incompatible assemblage of individual components. Constraints in synthesis are in the form of directives that prevent infeasible solutions from emerging. The knowledge base may also contain knowledge that helps to modify the knowledge depending on the context. This type of knowledge is stated as planning rules. This includes situations where a particular reordering of attributes is called for, or when multiple instances of a particular system are to be generated. In order to start the synthesis process, data are to be supplied by the user or by the expert system when it is used in a Knowledge-Based Expert System (KBES) environment. These data are referred to as preconditions.

Three examples are presented in this chapter to illustrate the synthesis process as applied to simple real-life problems. Following the description of the problems, the decomposition tree for each of the problems is illustrated in this section. The use of the software (GENSYNT) to obtain solutions for these examples is described in section 4.6.1.

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Example 1. Steel Industrial Building

The design problem is to obtain feasible structural configurations for the building. A feasible solution should include the type of trusses, their spans and rises, the roofing, siding, and end framing materials, and the number of bents and bay spacings. The components of a steel industrial building are shown in Figure 4.2.

Following the concepts of the synthesis model described earlier, the decomposition tree for the building is shown in Figure 4.3. The main system is *bldg_frame*. This is decomposed into its attributes and its subsystem *truss*. The *truss* system in turn is decomposed into its attributes. The basic data needed for the synthesis process are as follows: *nobays* (number of bays), *bldg_width* (width of the building), *length* (length of the building) and *rise* (rise of the truss). Any other constraints pertaining to a specific situation can also be stated and these are handled as constraints.

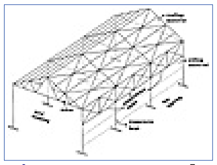


Figure 4.2 Steel industrial building

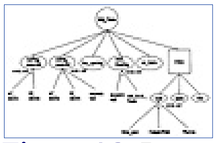


Figure 4.3 Decomposition tree for a steel industrial building

Example 2. Building Plan Layout at a Site

Consider another example of the layout of a building at a site of given length and breadth. The problem here is to determine (i) length and breadth of the building, (ii) number of floors required in the building and (iii) position and size of service cores. The service core houses the lifts, staircases, lobby, toilets, and fire exits. The resultant solution should be able to provide the necessary floor area in the building and the service cores should be able to house sufficient lifts to cater to the peak vertical transportation requirements. A simplified plan of a typical configuration of a building system is shown in Figure 4.4.

This example clearly demonstrates the issue of form versus function in decomposition. In the decomposition *goals* such as *core*, *length*, *width* and *area* are physical attributes of a building while a *goal* like *service* is a functional abstraction of the space that is to be set apart to locate the service components in the building. Both functional *goals*, viz., *service* and *goals* like *length* that describe the form of the artifact, are represented uniformly.

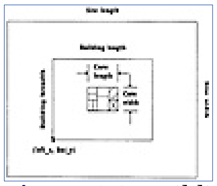


Figure 4.4 Building plan layout at a site

The decomposition tree for this problem is shown in Figure 4.5. Although *length* and *width* are continuous variables, from a practical point of view, only a few discrete combinations of these variables are considered for the building. The p-length and p-width attributes fix the length and width of the building, respectively, as a percentage of the maximum allowable dimensions. The actual dimensions are then arrived at by multiplying the maximum available dimensions by p-length or p-width as the case may be. For illustrative purpose, p-length and p-width are restricted to three possible values each. In the decomposition tree, FLOOR and S_AREA are treated as separate subsystems, although their attributes could very well have been treated as attributes of systems *building* and *service*, respectively. This is necessitated by certain implementation-related limitations of the software GENSYNT. This limitation as well as the details of the GENSYNT tool are explained in later sections.

The above problem has been solved using GENSYNT and the details are given in the next section.

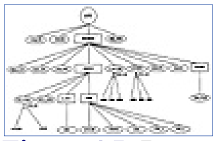


Figure 4.5 Decomposition tree for building plan layout

Example 3. Preliminary Design of a Gearbox

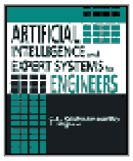
The purpose of the example is to design a gearbox, a typical line sketch of which is shown in Figure 4.6. The objective in this problem is to obtain the gear ratio for any stage subjected to the constraint that the ratio does not exceed 6 and it gets a value assigned from any one of the given standardised values. The gear ratio is the ratio of the output shaft speed (rad/s) to that of the input. The procedures are specified with an aim that the product of the synthesised gear ratios for the stages is closest to the user input. They also take care of the design parameters involving power transmission and synthesises the design subjected to user-given size constraints.

A standard pressure angle of 20° is considered for the gears. To ensure that there is no undercutting, the number of teeth on the pinion is taken to be 18. The gear ratio is one of the inputs from the user, which is further subjected to the constraint that the number of teeth is a whole number. Addenda of the gears are taken as one module. As a common practice spur gears are used. But if the gear velocity exceeds 400 rad/s the gear is generated as helical, in order to reduce the developed noise and vibration during the operation.

To simplify the problem certain assumptions are made as follows:

- Maximum number of reduction pairs is three.
- Module values are limited to 1, 5 and 10 (mm).
- Shaft material is assumed to be mild steel with a yield stress in shear of 150 MPa.
- In the case of hollow shafts the inner diameter is assumed to be 0.6 times the outer diameter.

The decomposition tree for the present problem is shown in Figure 4.7. The decomposition for the first gear row as shown in the figure holds good for the rest of the gear rows too. The problem has been solved using GENSYNT and the details are presented in section 4.6.1.



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4.4 Role of a Synthesiser in KBES Environment

From the foregoing discussion and examples, it is evident that the process of synthesis is very useful at the conceptual and preliminary design stages. In many of these situations the synthesis process will be advantageous compared to rule-based systems as it is possible to generate a number of feasible solutions. However, it must be emphasized here, that synthesis cannot be an independent process or activity within the overall design process but should form part of a knowledge-based environment. Thus, a module for synthesis should function as a generic module within an integrated system. A generic module is one that has a clearly defined function, is independent of problem domain and is repeatedly invokable. An inference engine is an example of a typical generic module. A module for accomplishing synthesis is termed a synthesiser.

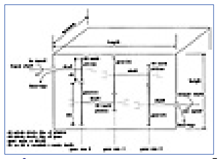

Figure 4.6 Line sketch of a gearbox

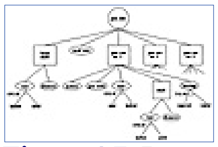

Figure 4.7 Decomposition tree of a gearbox

To function as a generic module, the synthesiser should be capable of functioning in two different ways as (a) a stand-alone shell for processing knowledge to generate alternate solutions and (b) a tool or generic component in KBESs.

Usually prototypes are built incrementally, and in an environment wherein different solution strategies are involved, it is necessary to be able to build and verify the various logical parts of the prototypes individually. In such a situation the synthesiser as a stand-alone shell will be helpful for processing design knowledge to generate feasible solutions.

As a generic component of KBESs, an inference engine can call upon the synthesiser from within a production rule to generate alternative solutions for a specific design goal. Therefore, in the context of KBESs, the synthesiser is a tool that is available to the knowledge engineer to accomplish tasks arising at various times during the inference process.

In a KBES environment, for the inference engine to invoke the synthesiser and for it to receive the output of the synthesiser, there must exist a common data exchange format. An examination of the storage of information in most expert system shells indicates that a hierarchy of objects in general is the most widely used way of representing a design solution as it emerges. For example, blackboard systems tend to represent the solution space as a hierarchy of objects on the blackboard. It is, therefore, desirable that the output of the synthesiser be a hierarchy of objects or frames (frame base).

Since the synthesiser is a generic module, it can be invoked at various levels of the solution process. Each time the synthesiser is activated, it can be visualised as contributing a part of the solution which is thus gradually built up. The synthesiser stores each feasible solution as a frame base. This frame base can be patched to the overall solution frame base by the inference engine whenever necessary. The inference engine can control the way the synthesiser functions and also pass on to it the required data and the necessary constraints to eliminate unwanted solutions. The inference engine can activate the synthesiser repeatedly by modifying the data and constraints passed to the synthesiser to obtain varying solutions. This ability is essential in simulating the iterative nature of this phase of design process. A typical rule-based environment supporting a synthesiser is shown in Figure 4.8.

4.5 An Architecture for a Synthesiser - A Generic Tool

It has been stated that synthesis can be accomplished in three possible ways. Of the three, only the problem reduction (decomposition-recomposition) approach is truly problem independent and forms an ideal platform for building a synthesiser. The architecture of a synthesiser is shown in Figure 4.9 [9,14,15]. The synthesiser is a closed system and has no knowledge of any problem domain, which is essential for making it problem independent. All input and output to the system are through files. The communication between the synthesiser and any other module in an integrated system is facilitated by a common file structure that is recognised by all the modules concerned.

Figure 4.8 Synthesiser in a rule-based environment

The input to the synthesiser is through two text files. The first one, called the decomposition file, contains domain-specific knowledge. The second file, called the preconditions file, contains problem-specific knowledge. The domain knowledge consists of a description of all the objects that can possibly constitute a part of the solution to the problem. Problem-specific knowledge contains data and constraints applicable to the particular application run. Typically, the decomposition file is prepared by a knowledge engineer in association with the experts of the problem domain. It remains unchanged for any particular problem definition. The preconditions file is prepared by the user or the design engineer specifically for the particular problem.

Figure 4.9 An architecture of a synthesiser

The synthesiser is an inference engine that operates on the knowledge base containing the domain decomposition. While a traditional production system represents the knowledge as rules, the decomposition represents the knowledge of the domain as a description of objects in the domain and their relationship. The representation of knowledge and the constraints are described below.

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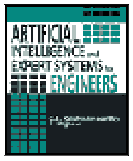

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Domain Decomposition and Its Representation

As noted earlier in the conceptual and preliminary design stages the designer must be provided with several alternative solutions. Evaluation of these solutions leads to the final choice of a solution. Hence, any computational model must be able to generate all possible solutions to the problem. However, to be computationally tractable, one must be able to dynamically prune the search in the solution space through constraints.

The decomposition model for the synthesis process has already been described in section 4.3. An artifact to be designed is decomposed hierarchically into systems and subsystems, finally ending into attributes. An attribute can be assigned a value, which may be an integer, real or string. When each attribute is assigned a value, we arrive at a solution by the process of recomposition. By assigning different values to attributes in a systematic manner we generate alternative solutions, as has been shown through an example in section 4.3. At this stage, it is necessary to deal with the syntax and representation scheme that are followed in the computer implementation of a generic tool. In the following discussion, the syntax followed in GENSYNT is used to illustrate the above aspects needed for development of a synthesiser. The details of GENSYNT are explained in section 4.6.

An attribute taking any ONE_OF values can be expressed as:

```
    attrname          ONE_OF     symbol 1, symbol 2,.......
```

The symbols are literal values that can be assigned to the attribute alternatively. For example, the siding material for the building frame (Example 1) described in section 4.3 is expressed as:

```
    siding_material   ONE_OF     AC_sheets, GI_sheets,
                                      masonry_wall.
```

In the domain decomposition, a system will consist of subsystems. In the above example, a building frame consists of truss as a subsystem. An attribute such as truss is called a SUBSYSTEM attribute to the main system. This is declared as:

```
    attrname          SUBSYSTEM  subsystem name
```

For the system building frame, the declaration of two attributes is given below:

```
 SYSTEM bldg_frame

 ....................................................

 siding_material   ONE_OF    AC_sheets, GI_sheets,
                                   masonry_wall

 ......................
 ......................
truss    SUBSYSTEM truss
```

An attribute to a subsystem is treated like any other attribute. When in its turn the attribute is to be assigned a value, the subsystem attached to the attribute will have to be synthesised entirely before the next attribute is taken up. This is the essence of the problem solution by the decomposition-recomposition approach. For example, in the subsystem truss (Figure 4.3), the attribute type is expressed as:

```
SYSTEM truss
type           ONE_OF      King_Post,
Compound_Fink,
                                          Warren
```

The ONE_OF construct can also be used to associate an attribute with different systems. In such instances, the attribute is synthesised by assigning different subsystems to the attribute at different times. The declaration is as follows:

```
attrname      ONE_OF       subsystem
1,subsystem2, . . .
```

For the problem of synthesis of system A, whose decomposition is shown in Figure 4.1, the syntax to be followed in GENSYNT is given below:

```
SYSTEM A

A1     ONE_OF          a1, a2
A2     ONE_OF          a3, a4
B SUBSYSTEM B

END_SYSTEM

SYSTEM B

B1     ONE_OF   b1, b2
B2     ONE_OF   b3, b4

END_SYSTEM
```

During synthesis the values of certain attributes require numerical computation, which may be performed through EXPRESSION, PROCEDURE or PROGRAM depending on the level of complexity of numerical processing involved.

If an algebraic expression is needed to express the value of an attribute, it is declared as follows:

```
attrmame         EXPRESSION              expression
```

The algebraic expression may involve design data, values of attributes of other systems and use of mathematical functions provided by the particular implementation of synthesiser.

For example, in the building frame system, the attributes no_bays and bay_spacing are expressed as,

```
     no_bays          EXPRESSION                nobays
     bay_spacing      EXPRESSION
      (length/nobays)
```

The attribute will be assigned the value returned by the expression at synthesis time. When the level of computation is not high and can be handled by using the in-built programming language provided by the implementation, the attribute can be of type PROCEDURE. If this is not possible, an external program may be called to do the computation and return the value to the attribute. Such attributes, which are assigned values returned by external programs are of type PROGRAM. These are expressed in the following form.

```
     attrname         PROCEDURE/PROGRAM          proc/prog-
                             name (arg1,arg2,...)
```

The first name defined in the decomposition file defines the whole artifact and is the one synthesised ultimately. It encompasses the entire design. The physical ordering of the other systems in the decomposition tree is not significant.

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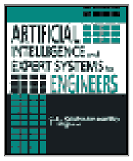

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Planning Rules

It can be seen that fundamentally there are two ways through which an attribute can have a value assigned to it. The first is selection from amongst a set of alternatives and the second is computation. Computation results in a distinct value that can be assigned to the attribute but selection is not always so obvious. In the example of the building frame, assigning the value masonry_wall to the attribute siding_material has no ambiguity associated with it. But assigning the value King_Post to the attribute type of truss subsystem raises a question. Precisely, how many trusses are there in the building frame? It is not possible to specify the number of trusses that a building has in the coding of the decomposition file since it depends on the context, i.e., problem data. During synthesis, we need to generate as many trusses as necessary. Such knowledge is expressed as planning rules. A system description may contain, in addition to the attributes, several planning rules which resemble IF_THEN rules in production systems.

Planning rules are of two types. The first type is used to generate multiple instances of a subsystem within a system when certain conditions are satisfied and has the following form:

```
IF      (condition 1 AND condition 2 And.......) THEN
FOR     index = expression 1, expression 2
REPEAT          system_name.
```

The second type has no conditions and is explained as,

```
FOR     index = expression 1, expression 2
REPEAT          system_name
```

For example, the planning rule for the building frame can be specified as,

```
IF      (bldg_frame. no_bents > 1)    THEN
FOR     t_count=1, bldg_frame.no_bents
REPEAT         truss
```

In the term bldg_frame.no_bents, *no_bents* is an attribute of the system bldg_frame. The dot operator specifies the path connecting the attribute to its parent system.

Constraints

In order to generate all possible solutions to a problem, the synthesiser has to assign all possible values to an attribute in a systematic manner in such a way that by changing the value of precisely one attribute in the entire solution process we arrive at an alternative solution. By this process we may arrive at solutions which are not acceptable or permissible. For example, according to practical considerations the attribute values of roofing_material and siding_material must be the same; otherwise the solution is not acceptable.

Such knowledge is expressed as constraints. In terms of the admissibility of a solution on which they are applied, constraints can be classified as *feasibility constraints* and *desirability constraints*. A *feasibility constraint* is a *hard constraint* and can either be *satisfied* or *violated*, and accordingly the solution is either *admissible* or *nonadmissible*. A *desirability constraint*, on the other hand, is a *soft constraint* and can be satisfied with *varying degrees of acceptability*. *Feasibility constraints* are applied during the synthesis phase while *desirability constraints* are applied during evaluation. Synthesis constraints that are not specific to any given problem are called static constraints. Static constraints are treated as part of domain knowledge and are included in the decomposition file. Typical static constraints for the building_frame example can be expressed as:

```
IF      (bldg_frame.roofing_material       = =
AC_sheets)
THEN    bldg_frame.siding_material   = = AC_sheets
IF      (bldg_frame.roofing_material = = GI_sheets)
THEN    bldg_frame.siding_material   = = GI_sheets
```

Constraints can also arise in a problem-specific manner. For example, the attribute roofing_material can be assigned the values AC_sheets or GI_sheets. If it is economically not viable in certain situations to use AC_sheets then we do not want solutions with AC_sheets generated. This constraint is specific to a particular application and such constraints are called run time constraints. The above constraint can be expressed as:

```
bldg_frame.roofing_material   ! =    AC_sheets
```

Run time constraints are part of a problem definition and thus form part of the data to the problem. They are thus specified in the preconditions file.

To enable flexible representation of various types of constraints, three forms of constraints are provided.

(i) Attribute constraints express explicit constraints on an attribute of a system with reference to the problem data. For example, if AC_sheets are not available or not preferable to use, this can be expressed as a constraint on the roofing_material as given in the above example of run time constraints. Such a constraint is attached to the attribute by the synthesiser. As soon as an attribute is synthesised, all attribute constraints attached to it are checked for. If any one constraint is violated, the solution being synthesised is aborted and the next alternative solution is taken up. There can be any number of attribute constraints for a particular attribute.

(ii) Meta constraints have the form:

```
IF      (set of conditions)
THEN    set of conditions
```

The set of conditions in the THEN part are imposed on the solution only if the set of conditions in the IF part evaluates to TRUE. The example of a static constraint given earlier is a meta constraint.

(iii) Constraint functions are the most powerful form of constraints available. They have the form:

```
function_name ( )
for example,  FAR_check ( )
```

Here FAR_check ( ) is a constraint that has to evaluate the Floor Area Ratio (FAR) of the building outline being synthesised and checks whether it violates permissible limits or not. FAR is defined as the ratio of the total area of the building footprint to the available site area. Building codes specify restrictions on this ratio and it is typically related to the number of floors in the building. It is quite evident that a mere expression would not be sufficient to specify this constraint and a function would be required to express it. Constraint functions can be used to handle such situations.

It can express constraints of any complexity. A constraint function returns either TRUE or FALSE to the synthesiser indicating whether the constraint has been met or not by the solution being synthesised. As explained later, the syntax of the function is similar to that of C language. Since the constraint functions are considered part of domain knowledge, they are included in the decomposition file.

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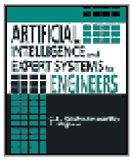

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Design Data

Design data includes all the data required to define a problem and is specified in the precondition file as follows:

```
Variable = value
```

In the building frame example, the *nobays*, *bldg_width*, *length* and *rise* need to be specified as design data. Such data is global and is used in expressions and passed on to procedures and external programs. The data can be either integer, real number or string.

4.6 Generic Synthesis Tool - GENSYNT

In the earlier section the issues to be addressed and capabilities to be provided for to perform the synthesis process by a generic tool have been discussed. An architecture has been presented along with a knowledge representation scheme that can be adopted by a developer of a system. While it will be beyond the scope of this book to discuss all the implementation aspects of the above architecture, a brief description of internal organisation of a Generic Synthesis Tool, GENSYNT, is given in Figure 4.10. This will help the reader to understand the functioning and usage of a synthesiser. In a later section, examples are presented to illustrate the use of GENSYNT [16].

Components of GENSYNT Knowledge modules

The domain knowledge consists of descriptions of all the objects that can possibly constitute a part of the solution to the problem. The implementation provides a structured language or syntax for representing the knowledge following the scheme explained in the previous section. A system description may also contain knowledge that helps to modify the knowledge depending on the context. This type of knowledge is stated as planning rules. These may also contain knowledge that describes an incompatible assemblage of certain systems. Such a knowledge is static and can be expressed as constraints. Detailed descriptions have been given earlier on the representation of planning rules and constraints.

The knowledge modules consisting of domain decomposition of the artifact, planning rules, and static constraints are expressed in specified syntax, which broadly follows the form given in the earlier section, and the file is called the *decomposition file*.

GENSYNT can be used to build a synthesiser in two different ways: (a) a stand-alone system and (b) a system that can be called from an expert system environment. In order to run the synthesiser, problem-specific knowledge is provided in a second file called the *preconditions file*. This consists of design data, run time constraints and special directives.

Examples are presented in the next section to illustrate the syntax followed in GENSYNT for preparing the *decomposition* and *preconditions* files.

Compiler

The compiler performs several functions. Firstly, it verifies that the decomposition and preconditions files are syntactically and semantically correct. The compiler issues relevant messages when it finds errors in the input files. Since the knowledge is represented as a network of objects, infinite loops are possible. These and other logical errors are checked for. Such errors are fatal and the synthesis process is not initiated.

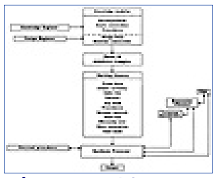

Figure 4.10 Internal organisation of GENSYNT

Synthesis processor

The synthesis processor is an algorithm that synthesises the solution based on a constraint-directed depth-first search through the goal tree. The synthesiser builds the alternative solutions one at a time. The solution tree is built by scanning the goal tree for an alternative solution path that had not been previously explored, and firing planning rules that occur at the node of that path. The solution space is called the hierarchy tree. The search is a depth-first search because it moves deeper into the hierarchy before completing a level. It is a constraint-directed search because it prunes a branch of the search space as soon as that branch violates a constraint. It is an exhaustive search because it generates all possible solutions to the problem.

Frame management system

During synthesis, systems are stored in memory as frames. The synthesiser stores the solution in memory as a frame base with the help of a Frame Management System (FMS) supported in an expert system environment. It dumps the solution in both text form and machine-readable form to disk files. If the synthesiser is activated from within an expert system the FMS has to regenerate the actual frame base in memory using these disk files when control returns to the expert system. The user can look up the file containing the solution in text form when the synthesiser is invoked as a stand alone or by an expert system. The FMS establishes the communication channel in an integrated design environment.

Language interpreter

The language interpreter interprets knowledge expressed as procedures in the decomposition. The implementation provides a language for writing simple procedures. Procedures resemble C functions generally. It is possible for procedures to access the frames created by the synthesiser, loop over the object instances, recognise current instances etc. It is possible to express certain constraints as constraint functions that need to be interpreted at synthesis time and this important feature is supported by the interpreter.

4.6.1 Application Examples

In the above section, the details of the knowledge representation scheme and the architecture of a generic synthesis tool have been presented. Particular attention has been paid to describe the various features incorporated and the syntax followed in a specific implementation of GENSYNT, a generic synthesis tool, in a KBES environment [9,16]. The user manual for GENSYNT is included in the diskette accompanying the book. The three examples presented in section 4.4 are used here to illustrate the use of GENSYNT for the synthesis process.

In order to activate GENSYNT, two files containing knowledge and data are needed. The first file, called the *decomposition file* contains the domain knowledge. The second file called the *preconditions file* contains problem-specific knowledge.

The structure of the decomposition file is as follows:

```
.TITLE
.DECLARATION
.DECOMPOSITION
.STATIC CONSTRAINTS
.END
```

The *preconditions file* contains the data and run time constraints.

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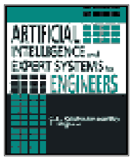

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Example 1. Steel Industrial Building

The components and the hierarchical decomposition tree of a steel industrial building are described in section 4.3. The decomposition file and preconditions file, following the syntax of GENSYNT, are given below. It may be noted that the synthesiser can generate 112 different solutions. The two static constraints and one run time constraint restrict the solution to the four given as output results of this problem.

```
TITLE Decomposition file for industrial building framework

SYSTEM
bldg_frame, truss

PROGRAM
nobents

DECOMPOSITION
SYSTEM bldg_frame

roofing_material ONE_OF    ACC_sheets,GI_sheets
siding_material  ONE_OF    ACC_sheets, GI_sheets,
                                 masonry_wall
no_bays          EXPRESSION      nobays
bay_spacing      EXPRESSION
                      (length/bldg_frame.no_bays)
end_framing      ONE_OF      masonry_wall,

 end_braced_frame
no_bents         PROGRAM
nobents(bldg_frame.no_bays,
bldg_frame.end_framing)

truss          SUBSYSTEM truss
```

```
IF      (bldg_frame.no_bents > 1) THEN
FOR     t_count=1,bldg_frame.no_bents
REPEAT truss

END_SYSTEM

SYSTEM truss

type    ONE_OF
 King_Post,Compound_Fink,Warren
span    EXPRESSION        bldg_width
rise    EXPRESSION        rise
END_SYSTEM

CONSTRAINTS
IF     (bldg_frame.roofing_material==AC_sheets)
THEN   bldg_frame.siding_material==AC_sheets
IF     (bldg_frame.roofing_material==GI_sheets)
THEN   bldg_frame.siding_material==GI_sheets

END

PRECONDITIONS
nobays = 2
bldg_width = 6.5
length = 8
rise = 1.8

CONSTRAINTS

truss.type==King_Post
```

<u>Output Results</u>

Solution No: 1

```
bldg_frame.roofing_material = AC_sheets
bldg_frame.siding_material = AC_sheets
bldg_frame.bay_spacing = 4
bldg_frame.end_framing = masonry_wall
bldg_frame.no_bents = 1
truss.type = king_post
truss.span = 6.500
truss.rise = 1.800
```

Solution No: 2

```
bldg_frame.roofing_material = AC_sheets
bldg_frame.siding_material = Ac_sheets
bldg_frame.bay_spacing = 4
bldg_frame.end_framing=end_braced_frame
bldg_frame.no_bents = 3
truss[1].type = king_post
truss[1].span = 6.500
truss[1].rise = 1.800
truss[2].type = king_post
truss[2].span = 6.500
truss[2].rise = 1.800
truss[3].type = king_post
truss[3].span = 6.500
truss[3].rise = 1.800
```

Solution No: 3

```
    bldg_frame.roofing_material = GI_sheets
    bldg_frame.siding_material = GI_sheets
    bldg_frame.bay_spacing = 4
    bldg_frame.end_framing = masonry_wall
    bldg_frame.no_bents = 1
    truss.type = king_post
    truss.span = 6.500
    truss.rise = 1.800
```

Solution No: 4

```
    bldg_frame.roofing_material = GI_sheets
    bldg_frame.siding_material = GI_sheets
    bldg_frame.bay_spacing = 4
    bldg_frame.end-framing=end_braced_frame
    bldg_frame.no-bents = 3
    truss[1].type = king_post
    truss[1].span = 6.500
    truss[1].rise = 1.800
    truss[2].type = king_post
    truss[2].span = 6.500
    truss[2].rise = 1.800
    truss[3].type = king_post
    truss[3].span = 6.500
    truss[3].rise = 1.800
```

Example 2. Building Plan Layout at a Site

The decomposition and preconditions files are given in Appendix II for the hierarchical tree for the problem shown in Figure 4.4. In order to simplify the presentation here, it has been assumed that the offset of the building outline from the site limits on all four sides of the site is the same. But in actual practice this is decided by the zonal regulations of the town-planning authorities. Also, only three possible variations of length and breadth are considered. They are fixed at 80%, 90% and 100% of the maximum dimensions. This is done by defining attributes p-length and p-breadth and specifying these three possible values through a ONE-OF relation. The number of service cores and their attributes are decided by using procedure-oriented programs. The aspect ratio and the slenderness ratio of the building are stated as static constraints. There are eighteen solutions possible and a typical solution is given in Appendix II under Output Results.

Example 3. Preliminary Design of a Gearbox

The maximum number of gear rows is restricted to three, to reduce the problem size. The decomposition and preconditions files are given in Appendix II. With the static constraints GENSYNT generated 12 feasible solutions out of the 72 possible solutions without the constraints.

The present example has the input of the overall length, breadth and height of the gearbox as 0.50 m, 0.50 m and 0.50 m, respectively. The input speed (in speed) is 400.0 rad/s and the output speed (out speed) required is 50 rad/s. The required power transmission is 40 kW. A typical solution is given in Appendix II under Output Results.

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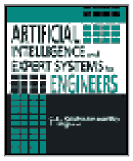

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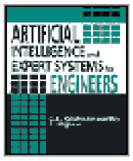

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Chapter 5
Criticism and Evaluation

5.1 Introduction

In many engineering domains, various feasible solutions can be generated for a given problem using the *synthesis* process explained in the previous chapter. Thus the outcome of the synthesis step is a set of feasible alternatives to the design problem. However, it is not possible to incorporate all the requirements and preferences in the synthesis process. As a result, such generated solutions, although feasible, do not satisfy all design objectives and hence need to be evaluated. This evaluation process is termed *critiquing*. It involves an evaluation of the proposed alternatives against a set of performance criteria to determine how well they meet the desired objectives.

As already mentioned in the previous chapter constraints applied during synthesis are *hard feasibility constraints* that check the admissibility of a solution. During the evaluation process, the *soft desirability constraints* are applied to check the degree of acceptability of the solution being critiqued.

Several large design problems in engineering require cooperative participation of multiple specialists from different domains. In general, each specialist is focused deeply in his own domain and tends to have limited knowledge of the other domains with which he must communicate and interact. In such situations the generated solutions need to be separately evaluated from each of the participating domains. The critiquing process is used here for evaluation through the expert knowledge of all the participating domains.

The following definition due to Fenves describes the role of a design critic: A critic is a tool or called as an agent in the same way that a synthesiser or analyser is a tool [1]. Its role is to apply to its input aspects, knowledge which is not available to the tool that generated or proposed the input aspect(s). Critiquing is best done by a source not directly connected with synthesising the solution. In an engineering context, where design is often a multiclient, multiparticipant problem, with each client or participant having a distinct set of requirements, it is not possible to incorporate every requirement and preference of each participating agent while synthesising a design solution [2]. Critiques may be provided from each of the client or participant domains that govern the final designed artifact. For the design of a large complex artifact, cooperative participation of several distinct agents is required and it involves application of a number of design critics, each of which represents a given agent's evaluation criteria.

In this chapter the methodologies available for critiquing a solution are briefly described. Critiquing is a knowledge-based activity and a framework can be devised to represent the knowledge pertaining to the critiquing of solution/s. Since design solutions have a hierarchical structure, critiques of individual aspects of the solution have to be hierarchically combined to determine the overall worth of the solution. An algorithm is presented here to combine the ratings of the evaluated items to arrive at the overall rating of the solution.

A complex design activity typically involves the application of several critics at various stages of the design process. Building each critic from scratch is a tedious process as the critiquing of the individual aspects of the solution and hierarchical aggregation have to be explicitly programmed. A generic framework is presented here and a particular implementation of GENCRIT (GENeric CRItiquing Tool) is described. The use of GENCRIT in a Knowledge-Based Expert System (KBES) environment is discussed with application examples.

5.2 Methodologies Used in a Knowledge-Based Environment

In a knowledge-based approach to engineering design, the design task is formulated as a search problem and some control strategy is applied to search through the state space to arrive at one or more solutions. In the decomposition-based synthesis process we generate solutions based on hierarchical decomposition and recomposition strategy and necessary constraints are incorporated to prune the search and to weed out infeasible solutions. However, in this process the constraints do not reflect the aspects to be considered from the other participating domains.

The basic strategy that can be used is *generate_and_test* where all possible solutions can be generated and tested to satisfy the given requirements [3]. Maher has modified this approach to *hierarchical_generate_and_test* through which partial solutions are generated and tested using the domain knowledge [4]. This is an example of *guided search* because of the use of domain knowledge in pruning correctly the search tree. This approach to design is exemplified in HI_RISE, a system for the preliminary structural design of multistory office buildings [4]. EDESYN is a domain-independent implementation of the hierarchical generate-and-test model that facilitates the development and use of a knowledge base for design [5]. EDESYN has been used to develop design expert systems like STRYPES, STANLAY and FOOTER that form part of a large design environment for integrated building design [6].

A variation of the generate-and-test model that has been successfully applied to design problem solving is the *constraint satisfaction* approach. In this approach, the evolving design is tested to see if constraints are violated [3]. The focus here is on how constraints are formulated and propagated as the design evolves. Luth et al. [7] proposed a framework for conceptual structural design and the framework uses a formulate-propagate-satisfy constraints approach to achieve the task. The constraints are classified as structural constraints and exogenous constraints. The knowledge modules for structural constraints deal with functional, behaviour, performance, geometry, product and reliability aspects of structural elements and systems. The exogenous constraints are constraints outside structural engineering and deal with architectural, mechanical, electrical and plumbing (MEP), constructibility and owner aspects that should be considered in the design process. The reasoning process generates alternative solutions and they are evaluated by using cost/value as a measuring yardstick. This model has been used to implement a floor framing generator for steel office buildings that are rectangular in plan [8].

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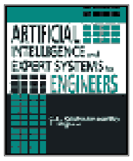

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The hierarchical generate-and-test and constraint satisfaction approaches do not address all the issues involved in cooperative problem solving. The *blackboard* architecture is recognised as one of the effective approaches to solve problems that require interaction with experts (knowledge sources) from different domains at every stage of evolution of a design. In this approach a global database called a blackboard is created and an emerging solution is posted on the blackboard. Different knowledge modules participating in the design process can evaluate or modify the solution similar to a team of experts looking at a solution from different perspectives/domains. The nature of involvement of participating domains in the solution process is thus opportunistic. These are well explained in references [3,9,10,11].

For qualitative evaluation of candidate designs, multifactor decision models have been proposed by Daru and Vanglis, Boer and Dong but these methods are not proved to be amenable for development of a tool for evaluation in engineering design process models [12–14]. Saaty introduced the Analytic Hierarchy Process (AHP) for modelling multifactor decision making [15]. In this process, the decision is decomposed hierarchically. The hierarchy reveals the factors to be considered as well as various alternatives in the decision. Then pair-wise comparisons are made, which result in the determination of factor weights and factor evaluation. The alternative with the highest weighted score is selected as the best alternative. In automated systems for preliminary design, the number and composition of the solutions are known to the critic only at run time. Therefore, an approach that calls for direct comparison of solutions is not suitable for implementation of design critics.

Concurrent engineering is emerging as an important knowledge-based approach in mechanical engineering. In this approach, while evolving/designing a product the various life-cycle issues, i.e., manufacturing, testing, installation, field tuning and maintenance, are considered. In the design process, one of the important tasks is to ensure compatibility of the elements/components with each other and satisfaction of various design specifications and constraints. Artificial Intelligence (AI) techniques have been used to develop a framework called Design Compatibility Analysis (DCA) [16]. The compatibility issues from different aspects mentioned above are represented in the knowledge base and the overall degree of compatibility of a proposed design is evaluated. The theory of fuzzy measure has been used by Ishii [17] to evaluate compatibility or the Match Index (MI) as the utility of design.

5.3 A Framework for Critiquing and Evaluation

In situations when we generate several feasible solutions and also in real-world applications involving interaction with different domain experts, it is necessary to have methodologies for critiquing and evaluating a solution. In the earlier works on knowledge-based systems for design of complex artifacts, application-specific strategies, rather than generic evaluation models, have been incorporated to meet the evaluation and critiquing requirements that need to be addressed during design.

Criticism involves evaluating a design in terms of its effectiveness in satisfying design objectives and constraints. Criticism is performed by subjecting the design solution to a series of tests that determine its degree of acceptance. In the multidisciplinary nature of a design task, the solution is subjected to criticism by each of the participating agents that are likely to influence it. A study of the critiquing process shows that the knowledge representation formalism and the methodology of evaluation can be independent of the domain which a critic addresses and the actual critiquing knowledge alone depends on the domain [18]. Hence, it is worthwhile to develop the necessary methodology and framework for criticism which will be domain independent so that this will enable us to build a generic critiquing tool that will minimise time and effort to develop critics for particular cases of application [19]. Before going into the details of critiquing methodology, the terminology used in this chapter is given below:

An *aspect* is an item of a solution that is to be critiqued.

Critiquing refers to the process of evaluation and can be used interchangeably with *criticism*.

Critic is an agent that performs the criticism.

Critique is an assessment made on an aspect. It consists of a *numerical worth* and a *textual remark*.

A *critiquing tool* is a generic framework used to build a *critic*.

The first important issue to be addressed in the development of a generic framework for critiquing is the representation of the designs. The representation should be generic enough to encompass a wide range of designs. Synthesis is the process that precedes critiquing or evaluation and we have seen in the earlier chapter that the artifact is decomposed into a hierarchical network of systems and subsystems eventually terminating to a functional or physical attribute. In such a case, components individually and through interaction with each other meet the design goals. Evaluation of such a design thus involves critiquing the individual components and their interaction with other components constituting the designed artifact.

Thus the interaction of participating attributes may involve any of the following cases:

a) Single (multiple) attribute(s) within a single component

b) Single (multiple) attribute(s) of instances of a component

c) Attributes of various different components

To identify the characteristics of critical evaluation aspects, a few typical aspects used for evaluation of a structural framing system are explained below.

Consider a structural framing system consisting of beams and columns as shown in Figure 5.1. The system is designed to carry vertical loads of a building and the decomposition tree of the system is shown in Figure 5.2(a).

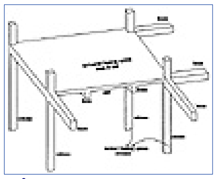
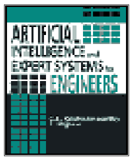


Figure 5.1 A structural framing system

Figure 5.2(a) Decomposition representation of the framing system

Length:

In the case of pre-cast construction, the beams are cast in factories and transported to the site of construction. The length of a beam is an important criterion which decides the transportability of the beam. Critiquing the aspect, viz., *length,* involves participation of a single attribute (*length*) of the component beam.



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Slenderness ratio:

The deflection of the beam, which is a serviceability conditions, depends on the length and depth of the beam. It is reflected by the value of the slenderness ratio, computed as length/depth. Thus the aspect of slenderness ratio involves interaction of two attributes, *length* and *depth* of the component *beam*.

Uniformity of beams:

This aspect is used for evaluating the economy of using the same form work for beams at a floor level. If the depths are different it becomes uneconomical. This critiquing aspect involves participation of one attribute *depth* of the various instances of the component beam.

Beam-column compatibility:

From a construction point of view it is desirable to have the same *breadth* for *beam* and *column* at a joint. The solution needs to be critiqued for this aspect of interaction of two attributes, viz., *breadth of beam* and *breadth of column* of the components *beam* and *column*.

The above aspects to be critiqued are shown in the hierarchical tree in Figure 5.2(b). The characteristics of the critiquing aspects can be categorised into the following four types:

1. Individual aspects - the aspects of this critiquing involve a single attribute of a component, e.g., *length* of the component beam.

2. Group aspects - the aspects that fall under this category are characterised by the interaction between two or more attributes within a component, e.g., *slenderness ratio* (length/depth where length and depth are the attributes of the component beam).

3. Metagroup aspects - this is the same as above except that the attributes participating belong to different components, e.g., *beam-column compatibility* (breadth of beam and breadth of column are attributes of two different components beam and column).

4. Multiple instance aspects - these aspects are characterized by the participation of a single attribute or group of attributes of all multiple instances of a component, e.g., *uniformity-of-beam*.

Critiquing Methodology

Having identified the categories of the critiquing aspects, the next task is how to apply the given critiquing criteria and arrive at an overall worth of the solution? The critiquing methodology to carry out the process is explained in the following three steps.

Figure 5.2(b) Various categories of aspects to be critiqued

1. Identify the dependencies specified in the artifact and represent the solution in a hierarchical tree form, for example, Figure 5.2(a) of the structural framing system for a building.
2. Rate the various aspects of the solution (each aspect may belong to any one of the four types) and place them at appropriate locations in the solution hierarchy. Figure 5.2(b) illustrates the aspects to be critiqued and their positions in the hierarchical tree. For each aspect to be critiqued, critiquing knowledge is expressed in a production rule format and a rating factor (RF) is assigned. Also it is possible the designer would like to assign different degrees of importance to the various aspects. This is assigned through weighting factors (WF) depending on the relative importance of each individual aspect to be critiqued. For instance, the engineer may assign more importance to the *length* of beams in the building frame example, from the point of view of cost of transport and serviceability considerations. The knowledge representation framework for this step is explained in the next section 5.3.1.
3. Combine the individual ratings and arrive at the overall rating of the solution. This is a very important step in the critiquing process. The ratings of the components are first arrived at by combining the individual aspects on the basis of their relative importance within the scope of corresponding components. Then the rates of components are combined based on their significance in the overall solution evaluation to arrive at the overall rating of the solution. This process of combining can be visualised as combining the individual ratings from the leaf-level nodes in the hierarchically represented solution tree to the root node, viz., the artifact. The overall rating thus obtained is the most appropriate estimation of the overall worth of the solution. The algorithm for combining the ratings is explained in section 5.3.3.

5.3.1 Knowledge Representation Framework

The knowledge base for a design critic consists of units of knowledge each of which contains the criteria on the basis of which a given quantity can be critiqued. Each knowledge unit, in turn, consists of *condition sets* that specify the critiquing criteria. The condition sets are expressed in the form of *rules*. A given quantity to be critiqued/evaluated is tested against these conditions.

Thus, the format for knowledge representation consists of the *name of the quantity* to be critiqued, a *WF* to specify its relative importance in the overall context and a number of *condition sets*, expressed in the form of rules, each of which assigns a *rating* (RF) and a *remark* (REMARK:) to the quantity if it satisfies the condition sets. A basic template for this format is given below.

```
< quantity to be critiqued / evaluated >: WF =<number>
IF (<condition 1>: AND <condition2> AND..........)
RF = VALUE
REMARK : < String in quotes>
```

The quantity to be evaluated can fall under one of the four classes of quantities listed earlier. The actual test to be performed to critique/evaluate the quantity is expressed in the condition sets, through rules.

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5.3.2 Inference Mechanism

The role of the inference mechanism in a critic processor is to apply the critiquing/evaluation criteria to the various quantities and assign ratings and remarks. In an engineering design environment a system is decomposed into component subsystems and attributes forming a hierarchical tree. Hence, while evaluating an item the processor simultaneously attaches the evaluated RF and WF to the various items in the hierarchy at their appropriate positions. Items of systems are attached just below the system of which they form a part. Metagroup-level items are attached at the same level as the highest system referred to in their attribute paths. Items under the *instances* head are attached at the same level of the tree as that of the instances themselves. In case the instances involved in the critique do not emanate from the same parent *system*, a fictitious parent node is created at the same level as the parents of the instances involved in the critique and the item is then attached below that node. Finally, the processor should combine the ratings of the evaluated items to get the overall rating of the solution. The combining algorithm is explained through an illustration [18,20].

5.3.3 Algorithm for Overall Rating of a Hierarchical Solution

The process of combining individual ratings and propagating the value up the system hierarchy is described below using a sample system network.

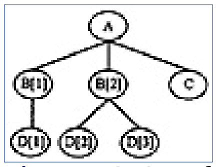

Figure 5.3 Sample solution tree

For purposes of illustration, consider the solution tree shown in Figure 5.3. In this tree:

A is the root node.

B[1], B[2] are two instances of a subsystem B of system A (artifact). C is another subsystem of system A.

D[1] is a subsystem of B[1], while D[2] and D[3] are subsystems of B[2].

In its first stage, GENCRIT assembles these components in memory as shown in the figure. *In GENCRIT* *syntax, components are named as systems.*

The second stage involves scanning the knowledge base and evaluating the items therein and simultaneously attaching these items to the solution tree. If after all items have been evaluated and attached, a particular system has no child nodes, it is removed from the tree. Figure 5.4 shows the solution tree after the second stage has been completed. In the figure, E[1] and F[1] are aspects evaluated under system D[1]. Similarly, E[2] and F[2] are evaluated aspects under system D[2], and E[3] and F[3] are aspects listed within system D[3]. H and I are metagroup aspects that represent interaction between systems B[1] and C, and B[2] and C respectively. J is an aspect that represents the interaction between multiple instances of an attribute of system D.

G is similarly an aspect that represents the interaction between the two instances of an attribute of system B.

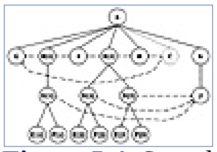
Figure 5.4 Sample solution tree after second stage of processing

Some points to be noted here are:

J represents interaction between multiple instances of system D. It therefore has to get attached to the tree at the same level as D. Since there is no specific node to which it can be attached, a fictitious node (denoted by K in the figure) is created at the same level as B and C. J then becomes its child.

G is similarly attached at the same level as B[1] and B[2]: as a node of system A. Since system C is not individually criticised, it is removed from the tree in the second stage.

The third stage of the critiquing process involves combining the individual ratings to arrive at an overall rating for the design solution.

The following notations are used to illustrate the combining process.

RF_x - Rating assigned by GENCRIT to the node represented by subscript x. For instance, RF_A is the rating of node A.

WF_x - Weighting factor associated with node x.

GENCRIT provides three separate ratings for the solution.

1. Minimum Rating - In this case, the parent node gets the minimum of the ratings of its child nodes. The net effect is that the overall rating will be equal to the minimum of all individual ratings. For instance,

$$RF_{D[1]}^{Min} = Minimum\ of\ RF_{E[1]}\ and\ RF_{F[1]}$$

2. Weighted average rating - Here, the rating of the parent is equal to the weighted average of the child node ratings.

$$RF_{D[1]}^{WA} = \frac{\sum_{x=E[1],F[1]} RF_x WF_x}{\sum_{x=E[1],F[1]} WF_x}$$

3. Maximum Rating - In this case, the parent node gets the maximum of the ratings of its child nodes. The net effect is that the overall rating will be equal to the maximum of all individual ratings. For instance,

$$RF_{D[1]}^{Max} = Maximum\ of\ RF_{E[1]}\ and\ RF_{F[1]}$$

The processor starts from the leaf level and traverses up the tree combining ratings at each level. With reference to the given example, the steps involved in arriving at the overall solution rating are:

- The ratings of E[1] and F[1] are combined to arrive at the rating D[1]. Similarly, ratings of E[2] and F[2] are combined to obtain the rating of D[2], and E[3] and F[3] are combined to arrive at D[3]'s rating.
- The ratings of D[2] and D[3] are combined to get B[2]'s rating. Since D[1] is the only child of B[1], the two nodes share the same rating.

- Similarly K gets the same rating as node J.
- As far as minimum and maximum ratings are concerned, the same process is repeated at the next level as well, to obtain the resultant rating of node A. For weighted average rating, at the level preceding the root node, an additional computation is performed.
- WFs only represent the relative importance of a node compared to the other child nodes of its parent. The depth of the tree, and hence the proportion of the solution represented by a particular node is not accounted for by WF. Hence at the level preceding the root node, the WF of the nodes are augmented by a factor which represents the portion of the solution carried by that node. In this example, B[1], B[2], G, H, I, and K are the child nodes of A. Two nodes (E[1] and F[1]) are descendants of B[1]. Four nodes (E[2], F[2], E[3], F[3]) are descendants of B[2]. J is the lone descendant of K. There are thus a total of 7 leaf nodes. Hence 2/7, which represents the fraction of the total number of leaf nodes below node B[1], is added to the WF of node B[1], 4/7 is added to that of B[2] and 1/7 is added to the WF of the fictitious node K. The modified WFs are then used to arrive at the weighted average rating of the root node A.

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5.4 Generic Critiquing Tool - Gencrit

In the earlier section a general framework for developing a critic processor has been discussed along with various aspects of critiquing methodology. In a KBES environment a critiquing tool can be used to build a critic that carries out either of the following two tasks.

(1) The critic can be used to evaluate a given set of solutions using the knowledge contained in the critiquing knowledge base and grade the solution in an order of preference. This is predominantly an evaluation task.

(2) In situations where interaction with more than one domain is involved, critics can be used to test whether a generated solution satisfies the criteria of other domains. This approach provides an alternate mechanism for handling multidisciplinary knowledge as compared to the blackboard framework where each knowledge source can opportunistically react to changes in the blackboard and a monitor enables this intervention.

A generic critiquing tool is needed in a KBES environment so that a process model for a prototype system can effectively make use of it. GENCRIT (GENERIC CRITIQUING TOOL) is one such tool developed for use in a KBES environment [21,22]. The architecture of GENCRIT is shown in Figure 5.5.

The main components that go into the functioning of GENCRIT are briefly described below and the syntax used for developing a critic is explained in the subsequent sections.

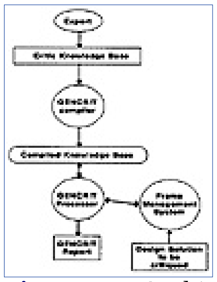

Figure 5.5 Architecture of GENCRIT

Critic Knowledge Base

GENCRIT's knowledge base is in the form of constraints that direct the processor to assign a certain rating and an associated remark to an aspect if a set of conditions is satisfied. The aspect to be evaluated may belong to one of the four categories explained in section 5.3.

Compiler

The GENCRIT compiler verifies that the critic knowledge base is syntactically and semantically correct. After performing the various checks it loads the contents of the knowledge base into relevant data structures in memory.

Processor

It is the inference mechanism of GENCRIT and the processor performs the task in three stages:

1. Loads the solution, which is stored in the form of a frame base in the disk, into memory and assembles the various systems of the solution in hierarchical form.
2. Evaluates the various aspects in the knowledge base and attaches them to the relevant locations in the solution hierarchy, along with their ratings and associated remarks.
3. Finally the processor combines the individual ratings to arrive at the overall rating of the solution.

In order to facilitate the reader to understand knowledge representation in the critiquing knowledge base, the structure and syntax followed in GENCRIT are briefly explained in the following section.

5.4.1 Critiquing Knowledge Base in GENCRIT

GENCRIT's knowledge base representation follows the framework of critiquing discussed earlier. The structure of the knowledge base is as follows:

```
TITLE
DECLARATIONS
CRITIQUING KNOWLEDGE
END
```

In addition the file(s) containing procedures in C language are to be linked with the GENCRIT library.

Title

Every knowledge base must have a title and the syntax is:

```
TITLE < title name of any length >
```

Declarations

All the systems, external programs and procedures used in the knowledge base must be declared to enable the compiler to ensure that logical errors are avoided. The form of a declaration is:

```
< type > <name 1>, <name 2>,........
```

where *type* can be one of SYSTEM, PROGRAM or PROCEDURE.

As it will be evident from the ensuing sections on GENCRIT's knowledge, system references in GENCRIT can be made either in the SYSTEM and METAGROUP knowledge segments or within procedures.

Critiquing Knowledge

The end of the declarations section and commencement of the knowledge section is demarcated by the keyword CRITIQUE. This is followed by the critiquing knowledge. Critiquing knowledge is specified under three heads: SYSTEM, INSTANCES, and METAGROUP.

SYSTEM critiquing knowledge pertains to critique on individual attributes of a system and on the interaction between attributes of that system. All the knowledge for a particular system is written under the heading SYSTEM. The systems can be arranged arbitrarily. The processor will scan the solution frame base and assemble the component systems in hierarchical form.

The syntax for describing the critique knowledge for a particular system is as follows:

```
SYSTEM <system-name> WF = <weighting - factor>
{
    <item>: WF = <weighting-factor>

    <value-1> = <procedure | external program>,
    <value-2> = <procedure | external program>,
}

IF(<condition-1> AND <condition-2> AND ...)
{
    RF = < value>
    REMARK: < text>
}
```

The various components in the system critiquing knowledge are described below.

WF

The WF is a number that signifies the relative importance of an item being evaluated, in comparison with other such items at the same level. Thus, if an item is relatively less significant or more significant than the other items at its level, it would have a WF less than 1 or more than 1, as the case may be. WF is an optional item. If no WF is specified for a particular item to be evaluated, GENCRIT assigns that item a WF of 1 by default.

Item

Within a system, the item to be evaluated may either be a single attribute of the system or the interaction between different attributes of that system. Every item has to have a name. Any valid symbol can be used to name such an item. The optional WF facilitates the user to specify the relative importance of the item. The attribute(s) of the system that contribute to the rating of this item figure in the constraints that follow its definition.

Value

For evaluation of an item various values need to be obtained from external programs or procedures. Such values can be defined as shown above and used in the constraints that check the worth of the solution critically. Any number of such values can be defined.

Constraints

Constraints encapsulate the criteria used to evaluate the concerned item. The constraints direct the processor to assign a rating and an associated remark to the item to be evaluated, if a set of conditions is satisfied. The syntax for a condition is

    <expression-1> <Logical operator> <expression-2>

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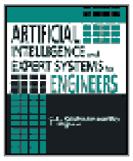

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RF

Each item gets a rating depending on which set of conditions it satisfies. The rating to be assigned to the item is specified by RF. Rating is a number between 0 and 100. A rating of 0 indicates complete unacceptability, while a perfectly satisfactory item evaluates to a rating of 100.

Remarks

The remarks are a qualitative translation of the significance of the rating. There is thus a remark associated with every rating. Remarks are stated in English text form. GENCRIT also facilitates printing of variable values within remarks.

While representing the critique knowledge, the developer must take care to see that the constraints are written in the order of increasing rating that he assigns to the item being evaluated. This is because GENCRIT makes no attempt to check that the conditions are mutually exclusive. Hence, it may happen that more than one set of conditions are satisfied. The strategy adopted by the GENCRIT processor when evaluating a particular item is to stop with the first set of conditions that is satisfied and assign the associated rating and remark to that item. By writing the condition sets in the order of increasing rating that they assign, the user can ensure that the first condition set satisfied is the one that assigns the least rating to the item.

When multiple instances of a system exist, critiquing knowledge needs to be specified only once. The processor automatically performs the evaluation as many times as there are instances.

Instances

Multiple instances of a particular system are a very common occurrence in engineering design. A common kind of critique in design relates to the interaction between several instances of one particular attribute of such systems. The items that are stated under the *INSTANCES* head pertain to this kind of criticism. The form of knowledge is represented as follows:

```
INSTANCES
SYSTEM <system-name>
{
    <item>: WF= <weighting-factor>
    [
          <value-1> = <Procedure>,
          <value-2> = <Procedure>,
    ]
IF (<condition-1> AND <condition-2> AND ...)
{
    RF = < value >
    REMARK: < text >
}
```

The values involved in the evaluation of items in this category are always obtained through procedures. This is because these quantities have to be obtained by cycling over all the instances of the system.

Metagroups

Quantities listed under the.metagroup category are used to state the critiquing knowledge pertaining to interaction between attributes across systems. The form of the metagroup knowledge is:

```
METAGROUPS
{
    <item> : WF = <weighting-factor>
    [
           <value-1> = <procedure | external program>,
           <value-2> = <Procedure | external program>,
    ]
IF (<condition-1> AND <condition-2> AND ...)
{
    RF = < value >
    REMARK: < text >
}
```

The conditions in the metagroup knowledge base can contain any attribute of any system. The attribute should be specified by its path. Path always starts at the immediate parent of the attribute. For instance, if the attribute *length* of the system *beam* is to form a part of a condition it is stated as *beam.length*.

One important task of the GENCRIT processor is to attach the metagroups to the system hierarchy at appropriate points. It does this by scanning the conditions to identify the attributes whose interaction is sought to be evaluated. By means of the specified path of the attributes, the processor identifies the systems being referred to in the conditions. After evaluating the item, it attaches it to the hierarchy at the same level as the "highest" system referred to in the conditions.

Procedures

Procedures are an integral part of the GENCRIT processor. Procedures are essentially meant to perform computations that cannot be done using *expressions*. These are represented in C programming language and linked with the GENCRIT's processor.

5.4.2 Working of GENCRIT

Criticism, as done by GENCRIT, is a three-stage process. In the first stage, the solution which is in the form of a frame base is loaded into memory and the component systems are arranged in their hierarchical order. The processor starts from the root node and performs a layer-wise construction of the system network. The network is assembled up to the level preceding the leaf-level nodes.

In the next stage, the processor scans the critique knowledge base and evaluates the various items mentioned therein. It simultaneously attaches these items to the hierarchy at their appropriate positions. Items of a system are attached just below the system of which they form a part. Metagroup-level items are attached at the same level as the highest system referred to in their attribute paths. In the case of metagroup items representing interaction between multiple instances of a system, the specified WF of the item is multiplied with a number equal to the number of instances of that system.

Finally, the processor combines the ratings of the evaluated items to get the overall rating of the solution.

Three ratings are provided by GENCRIT, viz., maximum rating, minimum rating and weighted average. The process of combining individual ratings and propagating these values up the system hierarchy is described in section 5.3.3 using a sample system network.

If after attaching the various evaluated items, the processor finds that a particular system has no leaf nodes attached to it, it removes the system from the network. This kind of situation arises when no attribute of that system plays any role in the performance of the synthesised solution. In such a case, no reference at all will be made of that system in the critique knowledge base.

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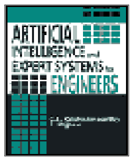

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Example 1

Consider the same problem of building planning addressed in Chapter 4. A typical solution generated by the synthesiser for the decomposition shown in Figure 4.5 (in Chapter 4) is shown in hierarchical form in Figure 5.6. We show how this solution can be subjected to criticism based on considerations not included in the synthesiser.

Four main criteria are used to critique the solution. These are *orientation*, *daylight and view*, and *efficiency of building*, which represent architectural criteria and *suitability for lateral systems* which is from a structural viewpoint.

Figure 5.7 shows the critiquing tree after the final stage of critiquing. The individual ratings and weights of attributes and the generated ratings for the parent systems and the root node on execution of GENCRIT's combining algorithm are given in Figure 5.7.

The actual critiquing knowledge is listed below.

```
TITLE A Critic that evaluates overall
                       office building configurations

SYSTEM
               site,
               bldg_system,
               service,
               core
CRITIQUE
SYSTEM service WF = 1.2
{
/* Item No. 1*/
suitability_for_lateral_system: WF = 1.0

               IF(core_location == center)
               {
                      RF = 100
                      REMARK: "Centrally located core can be used for \
                      placing lateral system"
               }
```

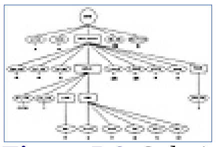
Figure 5.6 Solution critiqued

```
               IF(core_location != center)
               {
                       RF = 50
                       REMARK: "Core does not serve the additional \
                       purpose of serving as a lateral resisting system"
               }
}

/* Item No. 2*/

        daylight_and_view: WF = 0.8
               IF(core_location == center)
               {
                       RF = 100
                       REMARK: "This configuration provides \
                       window line access all around"
               }
               IF(core_location == sides)
               {
                       RF = 50
                       REMARK: "This configuration causes window line acce
                       to be denied to a significant percentage of its \
                       perimeter"
               }

METAGROUPS
/* Item No. 3 */

efficiency_of-building: WF = 1.3
[perc_utilisation=s_area.area*100/(building_system.length* \
                                                      building.width)]
        IF(perc_utilisation >= 25)
        {
                       RF = 20
                       REMARK: "Efficiency of utilisation of bldg is low"
        }
        IF(perc_utilisation >= 15 AND perc_utilisation < 25)
        {
                       RF = 60
                       REMARK: "Efficiency of utilisation of building \
                       is fairly high"}
        IF(perc_utilisation >= 10 AND perc_utilisation < 15)
        {
                       RF = 75
                       REMARK: "Efficiency of utilisation of building \
                       is fairly high"}
        IF(perc_utilisation < 10)
        {
                       RF = 100
                       REMARK: "Efficiency of utilisation of building \
                       is very good"
        }
/* Item No. 4*/
orientation: WF=0.8
        IF(site.orientation == NS AND bldg_system.length > \
                                                      bldg_system.width)
        {
                       RF=100
                       REMARK: "The building is ideally oriented for \
                       tropical climactic conditions"
        }
        IF(site.orientation == NS AND bldg_system.width > \
                                                      bldg_system.length)
        {
                       RF=50
                       REMARK: "The building is likely to get heated \
                       excessively as its longer \ edges are exposed
                                                      to sun"
        }
        IF(site.orientation == EW AND bldg_system.width > \
                                                      bldg_system.length)
        {
                       RF=100
                       REMARK: "The building is ideally oriented for \
                       tropical climactic conditions"
        }
        IF(site.orientation == NS AND bldg_system.length > \
                                                      bldg_system.width)
        {
                       RF=50
                       REMARK: "The building is likely to get heated \
                       excessively as its longer edges are exposed
                                                      to the su
        }
END
```

Example 2

In this example the details of a design critic developed using GENCRIT are presented. The design being critiqued is that of a single-story RC building. The example design solution that is to be critiqued from the point of view of ease of constructibility of the design is shown in Figure 5.8. Various aspects of the solution that influence the constructibility, like uniformity of longitudinal spacing, uniformity of transverse spacing, beam-to-beam compatibility, longitudinal beam-to-column compatibility, transverse beam-to-column compatibility, piping interference in same direction, and piping interference in across direction, are critiqued.

The building system in this example is decomposed into four major subsystems, viz., *lng_layout*, *trn_layoug*, *beam*, and *column*. The *lng_layout* and *trn_layout* subsystems are in turn decomposed into subsystem *bay*. The solution will then consist of several instances of these subsystems, viz., four bays in longitudinal direction, three in the transverse direction, nine beams and twenty columns. The representation of the solution after the first stage of criticism is shown in Figure 5.9.

Figure 5.7 Critiquing tree after final stage of critiquing

The items of the solution that are critiqued are explained below:

Uniformity of layout

When bays repeat, as will happen when the spacings are uniform, construction cost is considerably reduced.

Beam-column compatibility in both directions

If the dimensions of the beams and columns framing into each other at a joint are compatible, form work cost is reduced.

Beam-beam compatibility

When beams running in orthogonal directions meet at a joint the cost of form work can be adversely affected if they have different depths.

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Interference between piping systems and structural components in both the directions

The layout of pipes at the roof level of the building is handled by service specialists. If this task is done without proper communication with the structural specialist, the locations of the pipes can interfere with the beams at the roof level. Such interference may call for costly drilling of holes through beams to accommodate the pipes.

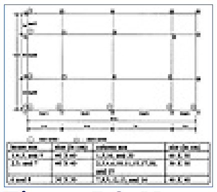
Figure 5.8 Network of beams in the RC building

The critiquing knowledge coded in GENCRIT syntax and procedures in ‘C’ are listed in Appendix II. The details regarding the attachment of evaluated items to the solution tree at the second stage and combining of individual ratings to obtain the overall rating in the third stage are presented in Figures 5.10 and 5.11. The two numbers against each item represent RF and WF, respectively.

Example 3 Preliminary design of gear trains

The objective is to critique the preliminary design of gear trains using GENCRIT which has been synthesised using GENSYNT. The solution critiqued is shown in Figure 5.12. The criteria taken into consideration during critiquing are *wear equalisation*, *contact ratio*, *factor of safety*, *sufficiency of maximum dimensions* given by the user as inputs to GENSYNT and *vibrational stability*. These criteria are not used in the process of synthesis.

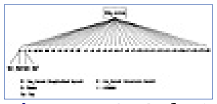
Figure 5.9 Solution after first stage

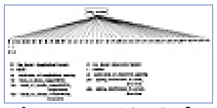
Figure 5.10 Solution after second stage

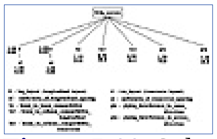
Figure 5.11 Solution after third stage

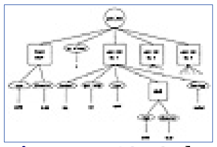
Figure 5.12 Solution tree which is critiqued

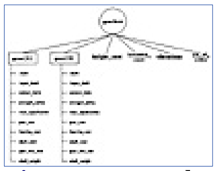
Figure 5.13 Solution after second stage

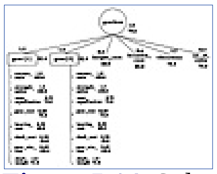
Figure 5.14 Solution after final stage

The parameters based on which critiquing is done are

- Gear cost: spur gears are cheaper than helical gears.
- Bearing cost: radial bearings are cheaper than tapered bearings.
- Shaft cost: solid shafts are cheaper than hollow shafts due to the machining costs involved.
- Gear size cost: The larger the module the larger the gear and hence the larger the cost.
- Shaft weight: A hollow shaft has lesser weight and hence is more vibrationally stable than a solid shaft.

Other items critiqued are explained along with the respective procedures.

Figures 5.13 and 5.14 show the solutions after the second and third stages of criticism.

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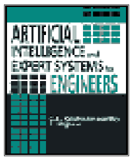

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Chapter 6
Case-Based Reasoning

6.1 Introduction

In the earlier chapters three AI-based techniques have been presented. Rule-based models are appropriate for domains where the knowledge can be represented in the form of heuristics or thumb rules. This technique is well suited for classification and diagnostics problems. In engineering design problems, the artifact can be decomposed into various systems and subsystems, and the subsystems and components can be designed separately from a suitable solution space. By combining the solutions of subsystems forming the systems and satisfying the compatibility requirements, many feasible solutions can be generated using the synthesis process. In multiclient problems the solutions generated by the synthesis process must be tested or evaluated for the satisfaction of constraints from different domains. This evaluation can be carried out by the critiquing process.

At this stage it may be worthwhile to analyse briefly the ways and means adopted by human experts to solve problems. According to Stephen Slade [1]: *An expert is one who has vast specialised experience, having witnessed numerous cases in the domain and generalised this experience to apply it to new situations. When confronted with a problem, the expert is reminded of previous similar problems and their respective resolutions. It might be that the expert has so many exemplary cases for a given problem that the experience has been distilled into a general rule to be applied. Still, this general rule has its root in actual experience. Hence it can be stated that the design expert derives the knowledge from experience and the basic unit of knowledge is case but not rules. Experts gain knowledge through accumulating new design episodes, remembering their own experiences and the lessons learnt from mistakes. They can reason by analogy and solve the new problems*.

Reasoning based on the similar past problem-solving experience helps the designer to exploit the useful details for application to a particular similar case. This problem-solving strategy is termed *case-based reasoning* (CBR) [2–4]. It is based on the observation that human reasoning processes are founded on specific experience rather than a set of general guidelines. Thus compared to other AI-based reasoning methods, CBR is a process of considering past cases and arriving at decisions on comparison between the current situation and the old cases. The solutions to problems are accomplished from past experience, stored in the form of cases, rather than from *rules* or *first principles*. That is, the case-based problem solver works by recalling what has happened in the past in similar situations rather than by projecting what could work in the future[2].

CBR provides many advantages to problem solving in a knowledge-based environment [5]. It allows one to propose solutions quickly, thus avoiding the long process of decomposition and recomposition involved in a synthesis process. It is useful in situations where the domain knowledge is not completely available or difficult to obtain. The past cases may help to provide warnings of potential problems that have occurred in the past and to avoid repeating the mistakes. However, it is to be emphasised that blind use of past cases to current situations should be avoided and knowledge/expertise is needed to transform or to adapt the past case to the current problem.

In this chapter the potential areas of application of CBR are discussed. The processes involved in CBR are explained. A framework is presented for building CBR systems and the use of a generic tool, CASETOOL, (CASE-based reasoning TOOL kit) in a Knowledge-Based System (KBS) environment is illustrated through an example.

6.2 Applications of Case-Based Reasoning

As discussed in the earlier section, CBR reduces considerably the time required for solving problems as it provides solutions from the past cases, thus avoiding the long inference chains typical of rule-based reasoning or the synthesis process. CBR has successfully been applied to a wide variety of problem-solving tasks in planning, design and diagnosis. In this section the potential of CBR application to various tasks is briefly described.

6.2.1 Planning

The process of planning is concerned with arriving at a sequence of steps or a schedule for achieving some desired state of the world [5]. The end result of the planning process is a set of steps to achieve the goal, satisfying a given set of constraints. The earliest case-based planner that was developed was CHEF [2,6,7]. The system CHEF creates new recipes based on the cases of recipes stored in its case base. The details of working and implementation of CHEF are described in reference [5].

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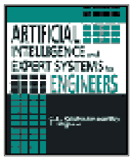

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6.2.2 Design

Typically, engineering design is identified as the process of problem solving where an artifact is designed to meet the functional, behavioural and other requirements. Thus it is a problem of finding a solution that satisfies a set of constraints which represent the requirements. It involves a wide range of domain-specific knowledge and requires considerable skills and experience to come up with concise and unambiguous specifications of the artifact to be designed [8]. The experience of an ‘expert’ which is gathered over a long period of practice may not be readily available in an organised and compiled form. In such situations it becomes difficult to apply the AI approaches such as rule-based reasoning for design. It is worthwhile to study how experienced designers (experts) approach and solve design problems. Experienced designers analyse the problem at hand to check whether it matches with any of the problems they have already solved. For this purpose, they compare the problem definitions, viz., requirements, conditions, constraints and other important aspects of the current problem with that of the past cases. Avoiding paths that led to undesirable intermediate results (encountered in the past problem-solving episodes), they generate solutions for the present problem from the past cases. It thus suggests that CBR is well suited for design problems which involve complex and multiple domain constraints as design cases provide illustrations of the way multiple domain constraints have been handled in solutions of the past.

Several case-based design systems have been built and reported in the literature. A few of the systems are briefly mentioned here. The system JULIA [5,9] plans meals. For landscape design CBR was used in CYCLOPS [10]. CBR combined with model-based reasoning is used in KRITIK and KRITIK-2 for design of small mechanical and electrical devices [11]. ARCHIE and ARCHIE-2 have been built to help architects in the conceptual design [12,13]. One of the systems that is used in industry is CLAVIER [14] which helps to arrive at a layout for aeroplane components made of composite materials for curing in an autoclave. DEJAVU [15] is one of the first domain independent and flexible systems developed to assist mechanical designers. There are three main components and they are (a) a knowledge base of design plans, (b) an evaluation module in the form of a design plan systems and (c) a blackboard-based adaptation system. A hybrid case-based design process model, CADSYN [16] uses CBR and knowledge base of domain decomposition (and constraints) knowledge for adapting design cases. This process model has been demonstrated through an example of a building design problem [17].

6.2.3 Diagnosis

In diagnosis, we are given a set of symptoms and asked to explain. A case-based approach can use the past cases to suggest explanation for symptoms and also to warn of explanations that have been found to be inappropriate in the past. One of the systems developed early is SHRINK [18] and has been designed to be a psychiatric diagnostician. The system CASEY [19] diagnoses heart problems by adapting the diagnoses of previous heart patients to new patients. It is to be pointed out here that the diagnostician cannot assume that a case-based suggestion is the answer. The suggestion must be validated. However, it is often found that validation of a suggested diagnosis is much easier than generation of a plausible diagnosis. In such kinds of domains CBR will be advantageous.

6.3 Case-Based Reasoning Process

In CBR the search is guided by previous problem-solving exercises which are stored as past cases and hence, solutions to the problems already solved need only to be retrieved rather than be computed again [20]. The key issues in CBR are

- **a)** the ability to identify the most appropriate case
- **b)** application of that case to the current situation
- **c)** storage of cases as complete patterns of experience including the reasoning process.

These issues are addressed in CBR process through the following three tasks [5]:

1. Case retrieval
2. Solution transformation
3. Case storing

The above three tasks are explained in the following sections.

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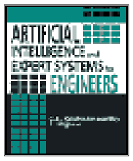

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6.3.1 Case Retrieval

The most important task of CBR is retrieval of appropriate cases. Recalling past cases is done based on the similarities between the current case and the past cases. It is possible that many cases may be available for a current problem situation. *How do we make the computer select the appropriate case for the current situation?* A case, in general, is a contextualised piece of knowledge representing an experience and it represents knowledge at an operational level; that is, it contains specific knowledge that was applied or the particular strategies that were applied for solving a problem. Thus, there are two parts of a case: (1) the knowledge it contains and (2) the context in which it can be used. It is this second part which is important for us to select or retrieve a case for a given context. One of the widely adopted techniques is to use *indices* for selecting cases.

Proper indexing of the cases is of critical importance for selecting relevant cases. There are several issues connected with indexing and the following points should be considered.

1. Indices must be truly relevant and predictive to enable selection of cases which fit the new problem requirements.
2. Indices must be generalised and be abstract enough to provide coverage for choosing all the closely fitting cases.
3. Indices should not be overgeneralised to include very loosely fitting cases.

In engineering design domains, the cases are characterized by various qualitative and quantitative governing factors leading to numerous details. The efficiency of CBR system depends on the efficiency of the case retriever. Various models of case retrievers are proposed by researchers working in this area. The retriever of ARCHIE [12,13] uses a literal string as an index, which encapsulates all the important aspects of a case. DEJAVU [15] and PANDA [21] also use similar retrieval techniques and have weightages associated with the important literal aspects of the case for determining the most suitable case. The weights of each matched aspect are added to score the event and the one with the highest score is chosen. The retriever of STRUPLE [22] has a means of checking the numerical values of governing factors during retrieval within suitable limits according to the given context.

While an exhaustive treatment of various techniques adopted for indexing and case retrieval can be found in the book by Kolodner [5], it is proposed to describe the method adopted in the framework of the generic tool, CASETOOL, for the CBR process in a knowledge-based environment [23]. The framework has been designed to address the issues concerned with engineering design.

A case retriever is a very important component of a CBR system as the efficiency of the system depends heavily on it. In engineering domains it is possible to group the governing attributes into qualitative and quantitative types. Depending on the type of attributes, procedures can be developed for determining the actual similarities of the retrieved cases with the current problem and potential failures associated with each retrieved case. Thus the case retrieval process is categorised into following three subtasks.

1. Deriving indices that reflect the important features of a given case which can be used for retrieval. The qualitative attributes are mostly used for assigning indices.
2. Weeding out remotely related cases which will not have any effect on solution generation. Quantitative attributes are used for this purpose.
3. Classifying cases into various categories based on the following considerations:

   (a) Similarities between old and current situations
   (b) Past performance of the retrieved cases as evaluated by critics.

The first subtask of identifying suitable attributes and arriving at proper indices is a knowledge-intensive job which has to be handled by the knowledge engineer and the domain expert. This is illustrated through an example in the next section.

The next two subtasks can be accomplished by developing a generic methodology applicable to various domains. In the framework of CASETOOL, the generic methodology involves three steps and they are as follows:

1. *Selection by search conditions*: Selecting a set of cases after weeding out all the loosely connected cases that are chosen based on index.
2. *Classification by relevance*: Classifying cases based on the degree of similarity between the given situation and the selected cases.
3. *Classification by performance*: Classifying cases based on the past performance.

Figure 6.1 shows the case retrieval process and the above three steps are explained below in detail.

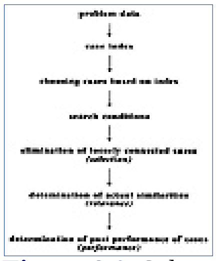
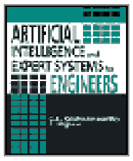

problem data
case index
choosing cases based on index
search conditions
elimination of loosely connected cases (selection)
determination of actual similarities (relevance)
determination of past performance of cases (performance)

Figure 6.1 Schematic diagram of case retrieval process

6.3.1.1 Selection by search conditions

In engineering domains, problems are defined in terms of functional requirements and design constraints. These are expressed through quantitative (for example, length, breadth, area etc.) and qualitative (for example, soil conditions, aesthetics, type of construction, manufacturing process, etc.) attributes. It is not possible to exactly reflect in the case index the quantitative attributes of a design solution. Hence, the cases that are selected based on case index may not be totally relevant to the given context. That is, when the attributes of the past cases are compared with that of the current problem, some of the cases chosen based on indices may be found to be loosely connected. Such cases need to be weeded out in order to select only those cases that are suitable for further processing.

Some domains are characterised by many governing attributes that are to be considered for selection of past cases. Comparing all these attributes at the same time to select past cases may become tedious. The process of selection can be made efficient by grouping the governing attributes into various sets and ordering these attribute sets for comparison in such a way that most of the irrelevant cases are weeded out early. In order to select appropriate cases, *search conditions* are set which specify acceptable limits of numerical values for quantitative attributes and the required properties/values for qualitative attributes. The task of deciding acceptable limits of numerical values and the required properties/values is knowledge intensive. Hence, the required value limits and properties for the governing attributes are set through a knowledge base.



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6.3.1.2 Classification by relevance

After weeding out loosely connected cases by the *selection* process, the *relevance* of the selected cases is determined in the next stage based on the deviation of attribute values of cases from that of the current situation and the relative importance of the attributes. Cases that are more relevant to the current situation are first determined for the solution generation process.

The similarity between past cases and the present problem situation is determined using *Relevance Norm* (*R*). The value of *R* is the normalised weighted least square estimation of deviations [24]. Let $v_1, v_2, v_3, \ldots, v_n$ be the values of *n* attributes of the past design case and $c_1, c_2, c_3, \ldots, c_n$ be the corresponding values of the current situation. Let $w_1, w_2, w_3, \ldots, w_n$ be weights (i.e., relative importance factors) of these attributes. Then *R* can be evaluated from the following equation,

$$R = \frac{1}{n}\sqrt{\sum_{i=1}^{n} w_i \left(\frac{v_i - c_i}{u_i - l_i}\right)^2} \qquad (6.1)$$

where u_i is the upper limit specified for *i*th variable and l_i is the lower limit specified for *i*th variable.

The cases are classified as *perfect* (approximately exact) and *close* (partial) matches based on the values of *R*. The limiting or range of values of *R* for classifying cases as *perfect* or *close* are domain dependent and, hence, are to be obtained through a knowledge base. The selected cases are ordered and taken up for solution transformation. This classification of cases using the relevance norm *R* is also helpful to decide later whether or not the new case should be stored in the case base. Since literal values of the governing qualitative attributes would have exactly matched with that of the current problem in the previous selection stage, only the numerical values of attributes are considered at this stage to compute the relevance norm and the classification of the extent of match, viz., *perfect* or *close*. Also, in engineering design domains as the governing attributes represent different properties of the design artifact and hence are associated with different units corresponding to the properties they represent (for instance, attributes that represent the property *angle* will be associated with *degree* or *radian* and those representing *length* will be in *meter* or *feet*), these attribute values will have to be normalised (i.e., converted to nondimensional value). Note in the above equation that the quantity $(v_i - c_i)$ is divided by $(u_i - l_i)$ to estimate the deviations in terms of a dimensionless value. $(v_i - c_i)/(u_i - l_i)$, w_i, and *n* are dimensionless quantities.

6.3.1.3 Classification by performance

It is necessary to have information/knowledge about the performance of the cases stored so that we can avoid situations that might lead to average and bad performances of the evolving solution. The design criticism and evaluation methodology described in the earlier chapter can be used to classify cases as *very good*, *good*, *average* and *bad* based on the rating assigned to a case by the critiquing process. The task of deciding on the conditions for classification is domain dependent and knowledge intensive. Hence, this is accomplished through a knowledge base. The performance classification is also used in the ordering of the cases to be taken up for solution transformation.

6.3.1.4 Illustration of the case retrieval process

As explained in the above subsections the task of the case retrieval process consists of the following steps: (1) indexing, (2) selection by search conditions, (3) classification by relevance and (4) classification by performance. The case indexing is a knowledge-intensive task and suitable schema have to be devised depending on the requirements of the domain of application. A generic methodology has been adopted for the remaining steps which enable us to carry out the two subtasks of case retrieval process: (a) weeding out remotely related cases using quantitative attributes through selection by search conditions and (b) their classification by relevance and performance.

The generic methodologies explained in sections 6.3.1.1 to 6.3.1.3 are illustrated through the following example.

Consider an artifact A shown in Figure 6.2 containing six components B, C, D, E, F and G, and thirteen attributes, *a*,*b*,*c*,*d*,......,*m*. The sample solution tree shown in Figure 6.2 is used here to explain the case retrieval process. Let *p*,*q*,*r*,*s*, and *t* be the governing attributes as they are important to define a case and w_p, w_q, w_r, w_s and w_t be the corresponding weights that define the relative importance of these attributes. If p_i, q_i, r_i, s_i and t_i are the values of these attributes for the *i*th case stored in the case base, then the three steps are carried out as follows.

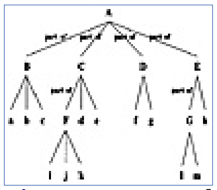

Figure 6.2 Sample solution tree

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Selection by search conditions:

The search conditions have to be specified for quantitative and qualitative attributes. Based on the domain knowledge, acceptable lower and upper limits for numerical values of governing quantitative attributes and the required literal values of qualitative governing attributes are specified as search conditions for weeding out the loosely connected cases. A check is made to see whether or not the corresponding numerical values of the past cases fall in the specified limits and literal values match with any of the specified literal values, and those cases that satisfy these search conditions are selected. Let *p* and *q* be qualitative, and *r*,*s* and *t* be quantitative governing attributes. These can be grouped into two sets, viz., *p* and *q* as the first set, and *r*,*s* and *t* as the second, for selecting the cases by weeding out loosely connected cases in two stages, first by checking the qualitative and then the quantitative governing attributes.

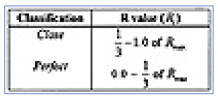
Classification by relevance:

Cases that successfully pass through the above *selection by search conditions* are examined to determine their relevance to the current situation. For the problem taken up for illustration here, w_r, w_s,and w_t are the weights for the quantitative attributes. Let v_r^i, v_s^i and v_t^i be the values of their attributes for case *i* and a_r, a_s and a_t be the values of the attributes *r*,*s* and *t* respectively. Then the relevance norm *R* for case *i* is calculated using equation 6.1.

$$R^i = \frac{1}{3}\sqrt{w_r\left(\frac{v_r^i - a_r^i}{u_r - l_r}\right)^2 + w_s\left(\frac{v_s^i - a_s^i}{u_s - l_s}\right)^2 + w_t\left(\frac{v_t^i - a_t^i}{u_t - l_t}\right)^2} \qquad (6.2)$$

where u_r&l_r, u_s&l_s and u_t&l_t are upper and lower limits specified for attributes *r*, *s*, and *t* respectively.

The retrieved cases are classified as *perfect* and *close* matches depending on the given allowable deviations in terms of R. For example, the conditions for classifying cases based on the deviations can be specified as given below.



Classification	R value (R^i)
Close	$\frac{1}{3} - 1.0$ of R_{max}
Perfect	$0.0 - \frac{1}{3}$ of R_{max}

where $R_{\max}$ is the maximum deviation calculated from the upper and lower limits specified as ranges for the attributes. A general expression for $R_{\max}$ is given below:

$$R_{\max} = \frac{1}{n}\sqrt{\sum_{i=1}^{n} w_i \left[\frac{\max.of\,(u_i - a_i)\ or\,(a_i - l_i)}{u_i - l_i}\right]^2} \qquad (6.3)$$

For the above example $R_{\max}$ can be evaluated as

$$R_{\max} = \frac{1}{3}\sqrt{\begin{array}{l} w_r\left[\frac{\max.of\,(u_r - a_r)\ or\ (a_r - l_r)}{u_r - l_r}\right]^2 + \\ +w_s\left[\frac{\max.of\,(u_s - a_s)\ or\ (a_s - l_s)}{u_s - l_s}\right]^2 + \\ +w_t\left[\frac{\max.of\,(u_t - a_t)\ or\ (a_t - l_t)}{u_t - l_t}\right]^2 \end{array}} \qquad (6.4)$$

Classification by performance:

One of the important features of the proposed CBR process is to use design criticism for retrieving cases. Each case in the case base has a critic rating associated with it. The rating is on a scale of 0 to 100 and is determined by critiquing the solution using a design critic prior to its storage in the case base. The critiquing knowledge and the linguistic values, viz., *very good*, *good*, *average* and *bad*, to qualify the critic ratings are provided by the domain expert. In this stage, based on the critic rating the case is classified under one of the linguistic heads suggested by the expert.

Let *case 1, case 2, case 3,* and *case 4* be the four chosen cases after the *selection* stage. After the *relevance* computation, let case 1 and case 3 be perfect matches and case 2 and case 4 be close matches. Figure 6.3 shows the various ratings of the retrieved cases. The values shown against the components are the ratings assigned by the design critic.

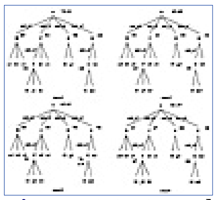


Figure 6.3 Sample cases

Let the following be the ranges prescribed by the expert for linguistic classification of cases.

Linguistic class	Critic rating
very good	75 – 100
good	50 – 75
average	30 – 50
bad	0 – 30

Considering the relevance and performance, the classification of retrieved cases is as given below.

case	relevance	performance
case 1	perfect	very good
case 2	close	good
case 3	perfect	average
case 4	close	good

The above classification is used for solution transformation and case storing. In the solution transformation stage, relevance classification will be used for taking a decision on the nature of modifications needed and the performance classification for anticipating the conditions causing poor performance of retrieved cases. Based on the deviations determined for the relevance classification, a decision is taken whether or not the evolving case is worth storing.

6.3.2 Solution Transformation

This addresses the second task of the CBR process: *How to build a solution from the retrieved cases?* As it is rare to find an exactly matching old situation, so the past solution needs to be adapted. There are four steps involved in the solution transformation:

1. Problem detection
2. Focusing on appropriate parts
3. Solution transformation
4. Evaluation and testing

These steps are described in the following subsections.

6.3.2.1 Problem detection

The issue addressed at this step is: *How to identify and avoid mistakes/problems that led to poor performance or failure in the similar past cases?* Some of the cases that are retrieved may turn out to provide a good solution or found to be associated with problems and failures. These cases are termed to be successful and failed cases, respectively. Failed cases are stored in the case base with feedback information about what went wrong and how to rectify them, if they are to be rectified. This information is useful as it warns the reasoner of the potential failure in similar situations and thus enables one in the reasoning process to avoid repeating the same mistake. Successful cases highlight the salient features to be concentrated upon for solution building. In the case-based system, the failed cases are given priority as avoiding the repetition of similar failures is more important [5].

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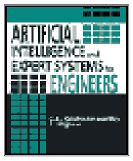

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6.3.2.2 Focusing on appropriate parts

This step precedes the solution transformation and addresses the issue: *How to handle large cases during the solution transformation?* In the engineering environment, due to problem size, the recalled cases could contain a very large number of components/attributes which are too cumbersome to handle. And, the retrieved case may find limited use in the sense that it may not be appropriate for all subgoals in the solution-building process. In such situations, the entire case need not be considered for case-based inference. Only those parts of the cases that are relevant to the current goal of the new problem need be scrutinised. Since both successful and failed cases are useful in the CBR process, focusing on the appropriate parts can be achieved in two ways: for a successful case, the current goal in the new problem decides the portion to be focused on; however, for failure, that part which caused failure should be studied.

6.3.2.3 Solution transformation

This addresses the issue: *How to build a solution from the past similar solutions?* As it is rare to find an exactly matching old solution, the past solution needs to be adapted. In general, one of the following four methods is used for solution transformation [5]:

1. Direct solution transfer [25].
2. Solution transfer with modifications.
3. Solution building using the same methods adopted in a similar previous case [26].
4. Schema-based solution transfer.

Application of each of the above methods depends on various factors. Method 1 is applicable if the old case fits exactly with the current problem (new case). Methods 2, 3 or 4 are adopted if the previous case does not fit the new case exactly. Method 2 is adopted when the old solution can be adapted with minimum modification. If the extent of modification is too large, method 3 is used. The solution-building methodology adopted in the previous case is transferred and a new solution is built. Method 4 is used in the absence of well-defined solution-building methodologies, by creating an abstraction of problem description from a few cases, extending it to fit the solutions of the previously solved problems and applying the schema to the new problem data to get a solution.

6.3.2.4 Evaluation and testing

In the last step, the issue addressed is: *How to validate the solution generated?* Here, the solution is evaluated to see whether or not it satisfies all the requirements and, thus, this step can be thought of as validation of the proposed solution [5]. This step is carried out by the following methods:

(a) Comparing and contrasting the proposed solution with other similar solutions

(b) Proposing hypothetical situations and checking the robustness

(c) Running a simulation and checking the results.

This process may require retrieval of additional cases and may result in *repair* of the proposed solution.

In situations where it is possible to try out the solution in the real world, a feedback about the real things that happened during the execution of solution is obtained and analysed. If the results are as expected, the solution will be stored as a successful case. Otherwise, explanations for the failures are built and the solution is stored as a failed case with possible suggestions to overcome such failures in the future (by storing the method adopted to rectify the solution along with the case). The testing stage helps in noticing the unforeseen opportunities and identifying the problems associated with the solutions.

6.3.3 Case Storing

The last task in the CBR process is to store the generated solution in the case base for later use. This task addresses the issue: *How to enhance the knowledge of the case-based system?* The differences between the existing and the new case are examined to determine whether or not the new case is worth storing as a case. This is an important task of the CBR process as the new case enhances the case base and thus helps future problem solving.

The new cases stored in the case base contain the problem description, solution details and the process adopted for arriving at the solution, including all the alternatives considered. Such details are very useful when modifications are to be made to suit the requirements of a future problem [20].

It is also worthwhile to consider storing the solution generated by other means, such as design experts, other computer systems etc. Such cases are stored in the case base following the representation scheme adopted in the particular case-based system.

6.4 A Framework for CBR in Engineering Design (CASETOOL)

From the description of the three tasks of the CBR process it is evident that it is possible to develop a generic framework which is domain independent. Such a framework will be useful to the developer of an integrated knowledge-based system for a given application. CASETOOL is one such generic framework developed [23] and implemented as an integral part of the KBES development environment DEKBASE [27,28]. The methodologies adopted in the implementation of CASETOOL for carrying out the three tasks of CBR, viz., *case retrieval, solution transformation,* and *case storing* are briefly described in the following subsections.

6.4.1 Case Retrieval

The methodology described in section 6.3.1 is implemented in CASETOOL for case retrieval. First a relevant group of cases is chosen based on an index. Indexing of cases for a particular application domain is knowledge intensive and it is discussed in section 6.3.1. An exhaustive search is carried out within the group of cases selected based on indices. Search conditions are represented as a range of numerical values for the quantitative attributes. This process of *selection* is well explained in section 6.3.1.1. The selected cases may represent a set of potential candidates that can be considered for case-based design. However, the selected cases may differ from the numerical values for certain of the attributes.

The *relevance* of the selected cases is determined from the actual deviations of the past cases from the current situation based on the deviations of the attribute values and then relative importance. This step is carried out through evaluation of the relevance norm described in section 6.3.1.2. Then, using design critics the performances of the selected cases are classified *very good, good, average* and *bad*, as explained in section 6.3.1.3. Figure 6.1 shows the various steps followed in the case retrieval process and the entire process has been illustrated through an example in section 6.3.1.4.

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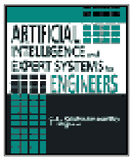

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6.4.2 Solution Transformation

The cases selected based on the case retrieval process may not match exactly with the current problem and the past solution needs to be adapted to meet the requirements of the current situation. This process is called solution transformation and as described in section 6.3.2. it consists of four steps:

Problem detection:

In the proposed framework the critical evaluation results as obtained from a critic (say for example using GENCRIT [29]) are stored along with the cases and are used as a basis for problem detection. The cases that are classified as *average* and *bad* during the case retrieval process are taken up and the conditions that are responsible for such poor ratings are identified. These conditions are used later in the solution transformation to avoid repetition of such conditions in the emerging solution. In a hierarchical representation, the low ratings are due to problems associated with certain components representing the subgoals of the overall design goal. Hence, the components that are associated with poor ratings are first identified and taking up such components is avoided at the solution-building stage.

Focusing on appropriate parts:

It is envisaged that the solution building/transformation will be done in a hierarchical representation, i.e., using the synthesis concept of decomposition. Hence, only those cases that are suited for the current subgoal in the solution transformation are to be focused on. The focusing on appropriate parts is done in two stages. In the first stage, the relevance and performance classification are used as criteria for focusing on the cases. The cases having perfect match are considered first and within the cases having perfect match, the one with a very good performance classification is taken up first. It may happen that a few cases that match with the current situation have similar relevance and performance classification, although the solution details may be different. Then it becomes very difficult to decide upon any one of these cases for solution transformation. In such cases, focus is centred on the component of the case corresponding to the current goal in the solution generation process. In the second stage of processing, the tie between the similarly matching cases is resolved by ordering them in the decreasing order of the rating associated with the corresponding component of the case.

Solution transformation:

The general methodologies that can be used for solution transformation have been discussed in subsection 6.3.2.3. In engineering design, hierarchical decomposition of a system into subsystems and components enables us to build up a system as described in Chapter 4 on Design Synthesis. In the CBR process, it is possible for a given situation that, we may retrieve more than one case. Based on the retrieved cases, appropriate parts from different cases can be combined to build the solution. This process is termed snippet synthesis [10,30] and the framework of CASETOOL can be used for this approach. When components of different cases are extracted and put together to form a system/solution the compatibility between these components has to be ensured. This is achieved in the proposed framework through a dependency net and constraint rules which simulate a multidisciplinary problem-solving environment. The solution obtained from past cases is checked to see whether or not it satisfies compatibility conditions. If it does not satisfy, either that particular part of the case is modified or the next available alternative is taken up. The process of generating a solution in the framework is shown in Figure 6.4.

The first component to be focused on for the current subgoal is taken up and checked for the conditions that might lead to poor performance and undesirable properties. If there exists any potential failure, the component currently considered is either modified or another competing alternative is considered for solution transformation. The modification is attempted first and if modification is not feasible, i.e., the knowledge for modification is not available in the knowledge base, the framework checks whether or not another component is available from another case. If it is, the process is repeated. When no component is available, the solution for that subgoal is obtained through other techniques such as rule-based inference or synthesis. Thus, every subgoal is solved and the overall solution is built incrementally.

Figure 6.4 The solution transformation

Evaluation and testing:

The framework currently supports only evaluation. Solution to the current problem is evaluated by the design critic, which can be developed using GENCRIT as described in Chapter 5. If any low rating is observed, modification is made to the component using the knowledge base [31], and thus information of low rating is also stored with the case for future use.

Testing has to be done externally, through simulation or field trial, and the feedback information is to be added to the case. This feedback information will be useful for problem detection, when we attempt to obtain a solution for a new problem/situation.

6.4.3 Case Storing

In the present framework, the relevance determined by *R* values, number of modifications made to the existing cases to arrive at a suitable solution, number of different cases that contribute to the evolving solution and design critic ratings are used as guidelines to decide whether or not a solution is worth storing.

If a case not generated by the system is to be stored in the case base, first it has to be represented according to the schema given in the subsequent section. Then the case should be critiqued by the design critics and stored appropriately in the case base.

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6.5 Architecture of CASETOOL

CASETOOL is a generic framework for CBR and has been implemented as an integral part of DEKBASE. The architecture of CASETOOL is shown in Figure 6.5. It has five processors RETRIEVER, ANTICIPATOR, TRANSFORMER, MODIFIER and STORER and other *functions* that are required for designing an artifact using CBR problem-solving techniques. These tools are activated through rule bases. Figure 6.5 shows various modules that constitute the CBR model and the interaction of CBR tools and rule bases.

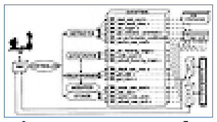
Figure 6.5 Architecture of CASETOOL

The **CONTROLLER** is a rule base which invokes other rule bases that constitute CBR modules. The three tasks of the CBR process, retrieval, solution transformation and case storing, are carried out by the following modules and functions.

RETRIEVER retrieves cases on the basis of a generated case index by invoking the function *CBR_load_case_card*. If a card is successfully loaded, it checks whether or not the name assigned to the current problem episode is unique by invoking *CBR_case_name_okay*. This step is important if the case has to be stored in the case base. Then to weed out loosely connected cases and classify the cases based on their relevance to the current problem and past performance, it first sets the attribute value ranges by invoking *CBR_set_ranges* and then specifies the classification conditions through the invocation of *CBR_set_relevance_conditions* and *CBR_set_performance_conditions* respectively. After setting up all the ranges and conditions, it invokes the function *CBR_search_case_card* to perform the three step retrieval, viz., *selection*, *relevance*, and *performance*.

After the case retrieval, the process control is switched to **TRANSFORMER**. It, in turn, invokes **ANTICIPATOR** and **MODIFIER** when required. For the goal under consideration, when the module ANTICIPATOR is called to assist TRANSFORMER, it first sets the ranges for certain aspects to be focused on by invoking *CBR_set_focusing_ranges*. Based on the feedback obtained from the focusing, it then arranges the cases in the order in which they are to be considered for problem solving by invoking *CBR_order_cases*.

Once this task is accomplished, to free the memory and make it available for the transformation process, it removes unwanted focusing information from memory by invoking *CBR_unload_focusing_ranges*. This step is important for those systems that are intended to run on platforms with less memory.

When the control is returned from ANTICIPATOR, the TRANSFORMER first checks whether or not cases exist to solve the current goal under consideration by invoking *CBR_check_case_exist*. If cases do not exist, the system requires another means (AI or other methodologies) to accomplish the goal. When cases exist, it obtains the name of the first case from amongst the cases under consideration for transformation by invoking *CBR_get_case*. With this information, it transfers the values required to the current problem by invoking *CBR_get_value*. This step of transferring values triggers the MODIFIER. The control is automatically transferred to MODIFIER which ensures the compatibility and suitability of those values obtained from past cases. Thus, the TRANSFORMER builds the solution subgoal by subgoal.

Finally when the control is switched to **STORER**, it ascertains whether or not the current problem episode is a new one and accordingly creates a new case card to store it by invoking *CBR_create_case_card*. Then it adds the new case to the case card by invoking *CBR_add_case*. It secures the new case card or the modified one, depending on the context, by updating the case base by invoking *CBR_update_case_card*. Once the case card is secured in the case base, it removes it from memory by invoking *CBR_unload_case_card* to enable the freed memory to be of use for other purposes.

The steps involved and functions to be called for building a case-based model using CASETOOL in the DEKBASE environment are explained in the Manual given in the diskette.

6.6 Application Example

In this section a case-based system, VASTU developed using CASETOOL, for planning rooms of a residential building is explained. This domain is chosen since it is familiar to engineers. However, planning a layout of a residential building for a given set of requirements is a complex task. A number of factors are to be considered such as lighting, air circulation, ventilation, heating and air-conditioning, privacy, etc. The expert architects, who deal with layout planning, prefer to use past similar episodes and try to adapt them to suit the current situation instead of trying to build the solution based on heuristics every time they face a design problem. A system developed using CBR helps to improve its performance by adding new cases, thus enriching the case base.

Developing a case-based system is more difficult since the number of tasks and their interdependencies are quite complex in the case of engineering design. CASETOOL through its interaction with the DEKBASE inference engine provides several functions as tools to address the several subtasks in the whole process. The main aim of presenting the case-based system VASTU is to demonstrate the features of CASETOOL, and, hence, its scope as given below is limited to placing various rooms in appropriate positions based on user’s requirements.

Scope and limitations of VASTU:

- Only single-story residential buildings with two to five bedrooms are considered.
- The number of bedrooms is decided based on the requirements of the occupants. However, the user can override VASTU’s decision by increasing and decreasing the number of bedrooms within the scope explained above.
- In the CBR process, only the case retrieval, anticipation and focusing on appropriate parts, solution transformation and case storing are explained. Due to the complex nature of the modification criteria, which requires knowledge about shape grammar and reasoning, only a brief description of the modification process is presented here, i.e., the module for modification is not included in the current version of VASTU.
- Since the main emphasis is placed on CBR, evaluation and testing modules are not included here. These can be developed using the GENCRIT tool described in the previous chapter.

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6.6.1 Architecture of VASTU

The architecture of VASTU is shown in Figure 6.6.

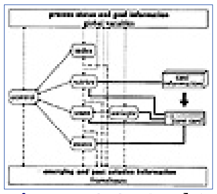
Figure 6.6 Architecture of VASTU

The system consists of six knowledge sources (KSs) which are represented through rule bases using DEKBASE and they are, **control**, **index**, **retriev**, **trans**, **anticptr** and **storer**. The knowledge source **control** is the one that controls the overall process. It schedules and monitors the entire process of layout generation for the given user requirements. It invokes **index** for deriving an appropriate case card index and then invokes search **retriev** to recall relevant past cases. The KS **retriev** sets various search conditions and selects those cases that are relevant to the current situation. When the KS **trans** is invoked by control, it first calls **anticptr** to set up conditions for focusing and anticipating.

On the basis of the specified order of cases to be taken up, **trans** adapts the solution to suit the current requirements. After completing the task of layout planning, the case is stored in the case base, if it is found useful for future problem solving. The various functions that are supported in CASETOOL for use by various KSs are given in Figure 6.5. The KSs and the description of functions that are used to build VASTU are given in the diskette accompanying the book. The CBR carried out by VASTU is explained in the following section.

6.6.2 CBR Process in VASTU

The CBR process in VASTU is illustrated through an example which starts with a user specifying the requirements as given in Table 6.1.

Table 6.1 The user requirements

Two bedroom house in a plot of 42ft × 30ft

Minimum plinth area required is 32ft × 20ft
Then plan outlay is Rs. 275,000.00
Both bedrooms with baths attached
Minimum size of first bedroom is 10ft × 12ft
Minimum size of first bedroom is 12.5ft × 10ft
Minimum dimensions of attached bathrooms are 6ft × 6ft
A living cum dining room with minimum dimensions of 14ft × 14ft
Minimum dimensions of kitchen room are 8ft × 10ft

(i) Case Retrieval

The case-indexing are knowledge intensive and hence needs to be represented using an appropriate schema. Table 6.2 gives the case indexing criteria adopted for this example.

Table 6.2 Case indexing criteria for single-story residential building

Case index	Total outlay	No. of bedrooms
type-1	Rs.200,000 to 300,000	2
type-2	Rs.300,000 to 400,000	3
type-3	Rs.400,000 to 500,000	4
type-4	Rs.500,000 to 600,000	5

The case indexing criteria are represented in the form of production rules and forms the KS module index. As explained in section 6.2, case retrieval involves three steps: (a) selection by search conditions, (b) classification by relevance and (c) classification by performance. For this example, the attributes needed for these three steps are grouped into three types and are given below:

Table 6.3 Template for case card representation

Group number	Step	Attributes	Relative importance factor (weight)
1	Selection	LivingDining Requirements Plinth Area SizeOfKitchen AreaOfBed[1] AreaOfBed[2]	
2	Relevance	PlotSize PlinthArea SizeOfKitchen AreaOfBed[1] AreaOfBed[2]	1.00 1.50 1.75 2.00 2.00
3	Performance	Rating	

Based on the user requirements of the illustration example, the module **index** will specify the case card index as ***type_1***. The case card for *type_1* contains six cases as shown in Table 6.4. The case cards are created following the template given in Table 6.3 and using the appropriate functions.

Table 6.4 (a) Cases in case card for type_1

case name	**Attributes**		
	LivingDiningRequirements	**PlotSize (sq. ft)**	**PlinthArea (sq. ft)**
seabrook	LivingCumDining	2350.0	810.0
ashram	LivingCumDining	1980.0	696.0
vhome	LivingCumDining	1728.0	777.0
santhi	LivingDiningSeparate	1584.0	660.0
manoj	LivingCumDining	1260.0	640.0
bangla	LivingDiningSeparate	1512.0	720.0

Table 6.4 (b) Cases in case card for type_1 (contd..)

case name	**Attributes**			
	SizeOfKitchen (sq. ft)	**AreaOfBed[1] (sq. ft)**	**AreaOfBed[2] (sq. ft)**	**Rating (sq. ft)**
seabrook	96.0	180.0	180.0	77.05
ashram	49.0	144.0	144.0	77.95
vhome	80.0	143.0	170.0	73.59
santhi	80.0	140.0	110.0	66.22
manoj	80.0	120.0	120.0	85.00
bangla	60.0	150.0	154.0	87.69

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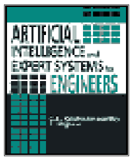

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(a) Selection by search conditions

The KS **retriev** retrieves cases by setting appropriate ranges for selection and conditions for classification. The attribute value ranges for selection of relevant cases are set using the appropriate function and for the current problem the values are given below in Table 6.5.

Table 6.5 Frame containing ranges for case selection

RangeData	**Position 1**	**Position 2**	**Position 3**
GROUP_NUM	1		
LivingDiningRequirements	LivingCumDining	LivingCumDining	
PlinthArea	640.0	640.0	704.0
SizeOfKitchen	80.0	76.0	84.0
AreaOfBed[1]	120.0	114.0	126.0
AreaOfBed[2]	125.0	118.75	134.25

The value of frame attribute GROUP_NUM is 1, which deals with attributes for selection. In the above table the Position 1, Position 2 and Position 3 are the three slots in the frame **RangeData**, giving scope for entering three values for the corresponding attribute. The search conditions are set by assigning values including upper and lower limits, and these are specified in the knowledge module **retriev**. For example, the qualitative attribute *LivingDiningRequirements* has been associated with the same value as that of the current situation for selection. For the quantitative attribute *PlinthArea*, the lower limit is taken as the current value itself (Position 2 in Table 6.5) and the upper limit is taken as 10% more than the current value (Position 3 in Table 6.5). Similarly, for the other three attributes, viz., *SizeOfKitchen*, *AreaOfBed[1]* and *AreaOfBed[2]*, the lower limit is taken as 5% less than the current value and the upper limit is taken as 5% more than the current value.

However, the magnitude of these percentages for fixing lower and upper limits is knowledge dependent and may vary from expert to expert. Based on these search conditions, VASTU selects case *manoj* as suitable for further classification.

(b) Classification by relevance

The process of setting ranges for relevance is similar to that of selection stage. For this purpose an appropriate function is used and the conditions for classifying the case as *perfect* and *close* are also specified. The ranges are set for attributes under Relevance (denoted by GROUP_NUM=2 in Table 6.3), and the values are as specified in Table 6.5. The classification conditions for relevance are set as given in Table 6.6.

Table 6.6 Conditions for relevance classification

Classification	lower R Value	Upper R Value
Perfect	0.0	0.071
Close	0.071	0.236

For the given problem R_{max} is calculated using Equation 6.4,

The R value of *manoj* is calculated using Equation 6.2.

Based on these values, and conditions given in Table 6.6, the case *manoj* is classified as *close*.

(c) Classification by performance

For the attributes categorized under performance (Group Number = 3 in Table 6.3) and the conditions for performance classification are specified through functions. The values used in the current examples are given below in Table 6.7.

Table 6.7 Values for performance classification

Classification	Lower rating	Upper rating
Very good	80.0	100.0
Good	60.0	80.0
Average	40.0	60.0
Poor	0.0	40.0

Based on the rating, the selected case *manoj* is classified as *very good*.

The plan of the retrieved case is shown in Figure 6.7 and its representation in frame base is given in Figure 6.8.

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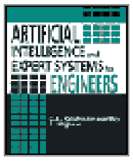

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(ii) Solution Transformation

Problem detection and focusing on appropriate parts - The current problem consists of six goals, viz., planning the six rooms - a living cum dining room, two bedrooms, two attached bathrooms and a kitchen room. For the current problem there is only one case available in the case base for layout planning. However, CASETOOL has a facility by which it can consider each instance of a component as a separate solution for the goal of that instance. For example, there are two instances of Bed Room and Attached Bath Room, respectively. Therefore, when trying to place the first instance of the current situation, the ordering of the components from case/cases may be such that the second instance will be taken up first. This situation may arise due to higher rating that is associated with the second instance. The goals and ordering of components are given in Table 6.8. The focusing and anticipating are done for each subgoal as explained below.

Living cum dinning room:

For the given problem there is only one case selected and this particular room does not have any other instance. Therefore, it does not require any focusing. However, if two cases are selected for any other situation, then the ranges for focusing are set through the rule base. The upper and lower limits are set such that interchanging of length and breadth are taken care of. The upper and lower limits that are stored in a frame base are given in Table 6.9.

Table 6.8 Ordering of cases for solution transformation

goal	cases	
LivingCumDining	manoj	
AttachedBathRoom[1]	manoj(AttachedBathRoom[1])	manoj(AttachedBathRoom[2])
BedRoom[1]	manoj(BedRoom[2])	manoj(BedRoom[1])
AttachedBathRoom[2]	manoj(AttachedBathRoom[1])	manoj(AttachedBathRoom[2])
BedRoom[2]	manoj(BedRoom[2])	manoj(BedRoom[1])
KitchenRoom	manoj	

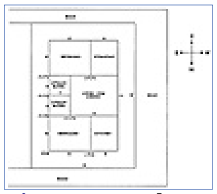

Figure 6.7 Plan of the retrieved case

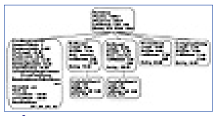

Figure 6.8 Representation of *manoj* in frame base

Table 6.9 Frame containing the focusing ranges for living cum dining room.

RangeData	**(Position 1)**	**(Position 2)**
LivingCumDining.Length	11.2	16.8
LivingCumDining.Breadth	11.2	16.8

Similarly, the focusing ranges are set for other subgoals, viz., BedRoom[1], BedRoom[2], AttachedBathRoom[1], AttachedBathRoom[2] and Kitchen Room. The values are given in Table 6.10.

Table 6.10 Focusing ranges for subgoals

Attribute	**Focusing ranges**	
	lower limit	**upper limit**
AttachedBathRoom[1].length	4.8	7.2
AttachedBathRoom[1].breadth	4.8	7.2
BedRoom[1].length	10.0	13.2
BedRoom[1].breadth	10.0	13.2
AttachedBathRoom[2].length	4.8	7.2
AttachedBathRoom[2].breadth	4.8	7.2
BedRoom[2].length	10.0	13.75
BedRoom[2].breadth	10.0	13.75
KitchenRoom.length	8.0	11.0
KitchenRoom.breadth	8.0	11.0

Solution transformation and modification:

In this stage, the solution is built goal by goal, i.e., placing one room after another, in the order given in Table 6.8. First, the left bottom coordinates of the living cum dining room are found out as (11,17) from the case *manoj* (Figure 6.7). Since this room is the first one, there will not be any interference. The next room to be taken up is AttachedBathRoom[1]. The location of this room is taken as (5,21). When the location of BedRoom[1] is taken up as the next goal, the part to be considered is BedRoom[2] of *manoj* (see Table 6.8) and the coordinates are (5,5) (Figure 6.7). Each time when the coordinates of a room are fixed (goals in this example), a heuristic check on interference is made whether the coordinates of the top-right and bottom-left corners fall within the room that is already transformed. Since the length and breadth requirements of BedRoom[1] are known (12ft and 10ft, respectively) the coordinates of BedRoom[1] are fixed. Since there is no interference, the modification module (not given here and is left as an exercise for the reader to develop) shifts the location of AttachedBathRoom[1] (bottom left coordinate, 5,21) to (5,15). Now when the next goal is taken up for locating the AttachedBathRoom[2], the left bottom coordinates are fixed as (5,21) and they do not interfere with any of the existing rooms. The next goal is to locate BedRoom[2]. From the case *manoj* the coordinates of BedRoom[2] are (5,5) which interferes with the first bedroom instance. Therefore, the modifier takes the next part as BedRoom[1] of *manoj* and fixes the coordinates as (5,27). The coordinates of the kitchen are fixed using *manoj*. At this stage of transformation the location of various rooms is as shown in Figure 6.9.

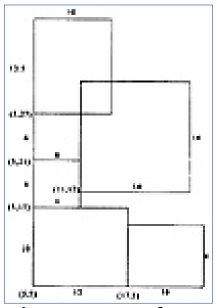

Figure 6.9 The modified plan

By using the knowledge module the solution is further modified in such a way that the rooms are adjacent to each other and are located as closely as possible. The modifications carried out are summarised in Table 6.11 and the final solution for layout of the building is shown in Figure 6.10.

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(iii) Case Storing

For the present example various rooms, except for the location and orientation of the first bedroom, have been adopted to suit the current requirements. However, since the entire solution has been obtained using a single case (viz., *manoj*) and the *R* value is less than 50% of R_{max}, the case is not stored in the case base.

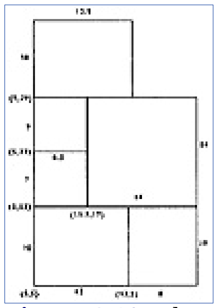

Figure 6.10 The transformed plan

Table 6.11 Summary of solution transformation

goal	solution from case	new solution	remark
LivingCumDining	(11,17)	(11.5, 15)	Location Modified
AttachedBathRoom[1]	(5,15)	(5,15)	Not Modified
BedRoom[1]	(5,5)	(5,5)	Not Modified
AttachedBathRoom[2]	(2,21)	(5,22)	Location Modified
BedRoom[2]	(5,27)	(5,29)	Orientation and Location Modified
KitchenRoom	(17,5)	(17,5)	Orientation Modified

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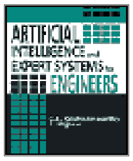

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Chapter 7
Process Models and Knowledge-Based Systems

7.1 Introduction

The preceding chapters presented different generic tools and techniques useful to engineering problem solving. Each tool or technique can be used only for those specific tasks for which they are ideally suited. For instance, expert systems are ideal for tasks involving reasoning based on heuristics and expert knowledge of the domain. Classification, diagnosis and monitoring types of tasks can be addressed efficiently using rule-based inference. This technique can also be used to develop front ends to many planning and design problems. Development of expert systems for diagnosis problems is illustrated in section 7.2 through a case study of one such system involving a complex knowledge net. Design synthesis is an ideal technique for generation of alternate solutions. The alternate solutions generated can be evaluated and graded using the critiquing tool. There can be instances, where solutions have to be generated or critiquing has to be done by comparing with already available successful solutions. Case-based reasoning provides the technique for carrying out such tasks.

Engineering Design

The engineering design domain has proved to be far more complex than the domains for which knowledge-based programming techniques were originally applied. One major source of complexity is that design tasks cannot be addressed through knowledge-based techniques alone. Although preliminary design tasks are characterised by the use of a large number of heuristics, some of the tasks require numeric computing using the algorithms pertaining to the execution of these tasks. Hence, a combination of procedural and knowledge-based techniques is required to address these tasks.

Multiagent and Cooperative Problem Solving

Design of any engineering system or component usually involves the participation of multiple specialists. In practice, each specialist is narrowly focused and tends to have limited knowledge of other domains with which the specialist must communicate and interact. The result is that even as the specialist approaches the design task in a manner aimed to achieve his/her local goals to the best possible extent, the same effort may not be reflected in the global objectives of the project. In other words, the best global solution should be evolved, after taking the concerns of all the participating agents into consideration. The globally acceptable solution will invariably involve compromises among the participants. The focus of recent research has been towards bringing together the *knowledge-based design systems* that are capable of performing well only in narrow limits and automated *integrated design systems* that have the ability to handle the entire design process. The main requirement for such systems is an organisational framework, in order to coordinate the activities of the individual modules of specialised expertise and also to guide and evaluate the composite global solution as it evolves, to ensure adherence with the overall objectives and satisfaction of concerns of all the participating agents. Various models have been proposed to organise the cooperative problem-solving environment with varying degrees of flexibility and philosophies regarding communication and control. One of the models used for this purpose is the *Blackboard model* and is explained in section 7.3 of this chapter.

Process Models

Another recent development is the attempt to develop explicit models of the design process. *Design process* models have resulted from research in design theory and have offered a new insight into the way integrated systems need to be developed [1]. The motivation for developing such models comes from the difficulty in developing integrated design systems using existing knowledge-based system development tools; the need to work within the capabilities of the development tool can be too constraining. The contention is that the more appropriate approach would be to conceive a model of the design process and then develop a computing framework for the realisation. of the model as a computable entity. This framework can then be used to develop the integrated system. A *design process model* attempts to structure the design process at an overall level by defining the activities that comprise it. At the task level, the model advocates the use of a design methodology that allows reasoning and creativity within that formalised representation of design. Knowledge-Based Systems (KBSs) developed based on explicit *design process models* do not suffer from the limitations faced by earlier integrated systems.

Integrated KBS Development

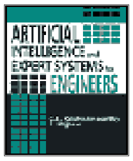
In order to build an integrated KBS the right approach is to undertake a detailed *task analysis of the domain* which involves detailed examination of the various tasks and subtasks of the entire design process for the domain and identification of the issues that need to be addressed to arrive at integrated solution(s). Based on the task analysis, an explicit *design process model* can be abstracted. Appropriate Artificial Intelligence (AI) methodologies and tools can then be identified for realising this model as a computing framework. This framework can then be used to develop an integrated system for the chosen domain problem. Case studies of three KBSs are presented in sections 7.4 to 7.6 to illustrate the development process involved in building integrated systems.

Other Methodologies and Techniques

Engineering design problems do not have unique solutions and an exhaustive generation of all feasible solutions using traditional Knowledge-based techniques can be quite inefficient unless sufficient constraints can be applied early in the generation process to prune infeasible solutions. Recent research has shown that Genetic Algorithms (GA) can be used to develop efficient methodologies for arriving at optimal design solutions. In the development of ODESSY described in section 7.4 the GA-based methodology has been integrated in a knowledge-based framework leading to a hybrid model for arriving at optimal design solutions. The new trends in the use of GAs leading to evolutionary computing and the promise it holds for a wider role it can play in engineering design are described in section 7.7.1.

One of the problems cited with generalised problem solving using expert system approaches is the difficulty involved in eliciting knowledge from experts. The ability to generalise from specific problem-solving knowledge is now being recognised as a desirable feature of automated systems. It is in this context that Artificial Neural Networks (ANN) have gained importance. Research and development work is in progress in integrating knowledge-based techniques into ANNs. A brief introduction to ANN and its potential when used in a KBS environment are given in section 7.7.2.

In the concluding section of the chapter, attention is focused on *Concurrent Engineering*, which is emerging as a new methodology that offers potential for developing integrated systems to meet the future needs of the engineering industry.



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7.2 Expert Systems for Diagnosis

REPCON is an expert system developed for diagnosis of causes of distress in buildings in distress and suggestion of repair methods [2]. Issues involved in its development, such as organising the domain knowledge, evolution of knowledge nets pertaining to defects in masonry walls and transformation of knowledge nets into rules, are presented in this section. The objective of the presentation is to give the readers an idea about the steps that one has to go through in the process of developing an expert system. The system is intended to assist building repair consultants and township maintenance engineers, who are increasingly being called upon to solve problems associated with strengthening, modification, repair and renovation of buildings. Evolution of knowledge nets and their transformation to rules for one of the knowledge bases on *Cracking in Brick Masonry* are briefly presented here.

7.2.1 Understanding of Domain Knowledge

Cracking is common in brick masonry construction, irrespective of whether the building is constructed entirely with brick masonry or whether it contains extensive masonry components. Hence, it is appropriate to incorporate a more elaborate and detailed knowledge base for this in the expert system. In fact, the major thrust of this developmental effort was to study and structure the complex knowledge of the domain. To structure the knowledge base, a proper understanding of the following factors is essential.

- First, the function of the structural subsystem affected by cracking should be understood. For instance, a wall can be either load bearing, or be an infill in a reinforced concrete frame or be a free-standing wall. Furthermore, it should be known whether the wall is external, internal, partition or just a panel wall.
- The shape of the crack can be vertical, horizontal, diagonal, random or ripping.
- Location of the crack.
- Extent of the crack.
- Activity of the crack (whether the crack is active or dormant).

With the years of cumulative experience of various experts and from the published literature, it is possible to speculate on the locations that are most vulnerable to cracking in any particular subsystem. One can also link the occurrence of cracking in these locations to its possible cause. For instance, in external walls of a load bearing structure, vertical cracking occurs most commonly at the corners of a side wall of a long building, near the quoins in the front elevation of a long building having short return walls, at the corners of the topmost story of a building with a reinforced concrete roof, below window jambs, around balconies etc. In a particular instance, if it is known that vertical cracks are located near a balcony, it can be safely inferred that the probable cause is drying shrinkage and thermal movement of the wall and the floor around the balcony, leading to cracking.

7.2.2 Evolution of Knowledge Nets

Having diagnosed the cause, one has to select an appropriate method of repair from among the wide variety of choices available. Generally, cracks in brick masonry are repaired by grouting and sealing with various types of mortars depending upon the type of materials used in construction, stitching with reinforced concrete or metal ties or sealing with bitumen. Also in particular cases, one may need to undertake remedial measures in addition to repair. The major factors that weigh in the choice of a proper repair and remedial method are (1) width of crack; (2) activity of crack (whether the crack is active or dormant); (3) type of bricks used (whether absorbent or non-absorbent); and (4) type of mortar used (whether relatively rich or weak).

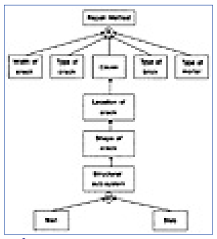

Figure 7.1 Static net for diagnosis and suggestion of repair method

Knowledge nets are evolved over two distinct stages. First, the net representing the conceptual structure of the knowledge base is constructed. It may be composed of one or more context types. This is called a static knowledge net. Figure 7.1 shows the static net for *cracking in brick masonry*. It is a structured framework established for the diagnosis and suggestion of a repair method for cracking in brick masonry. The static net was used to guide the evolution of the instance net. For this, each node in the static net is initialised with all the possible parameters. The resultant net, called the instance knowledge net, reflects the structure of the static knowledge net and represents the paths that could be taken during the consultation interaction. For developing the instance net, the node *structural subsystem* was instantiated first, including all its context types. Further, each of the context instances were developed fully, one by one, up to the node *cause*. Figure 7.2 illustrates the evolution of the instance net from the static net for an example data set. The transformation of instance net to rules was done simultaneously. Based on the experience during implementation, the instance net was refined further, incorporating suitable revisions. Once this part of the knowledge base was validated, the net for the next instance was constructed. The complexity of the knowledge was thus dealt with by the incremental evolution of the instance net, followed by its representation as rules, implementation and feedback leading to the final refinement of the net.

Further, having constructed the knowledge net for the diagnosis of *cause*, the instance net was then expanded further up the static net, up to the goal node, i.e., *suggestion of repair method*. This part of the knowledge was relatively simple compared with the complexity of the diagnostic process.

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7.2.3 Transformation of Knowledge from Nets to Rule Base

In the initial stages of construction of knowledge nets, it was decided to use rules for representing knowledge. Several factors weighed in favour of using production rules for knowledge representation.

As is evident from the static nets, the root node of all the knowledge bases in the system is *repair method or remedial measure*. This node is represented as the goal of the rule base. An example rule is given below.

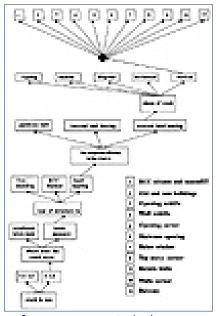
Figure 7.2(a) Instance net showing a typical path (contd..)

```
RULE    for active cracks due to movement of ground
IF      cause IS movement of ground
AND     confidence (cause) < 75
AND     type of crack IS active
AND     crack width in mm > 1.5
THEN    repair method suggested IS flexible apron
AND     DISPLAY method of repair in detail
```

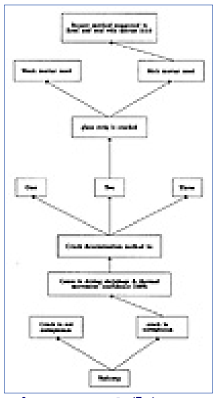
Figure 7.2(b) Instance net showing a typical path

Having identified the goal of the system, one of the goal instances, i.e., one of the repair methods, was considered. Rules were developed to lead this conclusion. Rules were added for other repair methods, interactively, observing the effects of each and modifying the previous rules as necessary. If a postulate was found to be common to many of the rules, it was made as an intermediate hypothesis. These changes were also incorporated in the knowledge nets. Only one single line of reasoning is shown in the Figure 7.2.

Confidence factors were used in REPCON to handle inexact reasoning based on uncertainty in the knowledge. Four typical rules with different confidence levels for the same conclusion are given below, in order to illustrate how uncertainty in knowledge is represented with the help of confidence factors.

```
RULE    cause2

IF      problem IS vertical crack near corner of side wall
AND     crack starts from DPC level and travels upward
OR      there is a difference in level on two sides of crack
OR      width of crack IS varying with temperature
THEN    cause IS thermal expansion aggravated by
        moisture expansion CF 60

RULE    cause3
IF      problem IS vertical crack near corner of side wall
AND     crack starts from DPC level and travels upward
AND     there is a difference in level on two sides of crack
OR      width of crack IS varying with temperature
THEN    cause IS thermal expansion aggravated by
        moisture expansion CF 75

RULE    cause4
IF      problem IS vertical crack near corner of side wall
AND     crack starts from DPC level and travels upward
AND     there is a difference in level on two sides of crack
AND     width of crack IS varying with temperature
THEN    cause IS thermal expansion aggravated by
        moisture expansion CF 90

RULE    cause5
IF      problem IS vertical crack near corner of side wall
AND     crack starts from DC level and travels upward
AND     there is a difference in level on two sides of crack
AND     width of crack IS varying with temperature
AND     building constructed in cold weather
THEN    cause IS thermal expansion aggravated by
        moisture expansion CF 100
```

Altogether the system contains 645 rules There are 16 graphical display screens for obtaining the data about crack patterns and location of cracks from the user. Twenty-one textual explanation screens are there to provide more details on the causes and repair methods.

7.3 Blackboard Model of Problem Solving

In production rule systems, the entire domain knowledge is represented as IF-THEN rules only. When the domain is very large and complex, production rule representation and associated inference lead to a large and inefficient knowledge base causing very poor focus of attention. The example problem presented in Chapter 3 on ‘Planning and Design of Steel Industrial Structures’ illustrates how a production rule-based system is developed for such a complex problem. The same problem can be designed in a more efficient manner using blackboard architecture. The difficulties posed by a large and inefficient knowledge base and poor focus of attention in production systems are overcome in the blackboard model, in which the domain knowledge is decomposed into smaller modules called knowledge sources, and a dynamic and flexible knowledge application strategy is used. The same concept can be extended to problems requiring involvement of multiple agents representing different domains. Many design problems in engineering fall under the category of multiagent problem solving, in which a solution proposed by one agent may not be acceptable to other agents. The blackboard model reacts as and when conflicts arise during problem solving and uses conflict-resolution knowledge sources in an opportunistic manner. Essentially, the blackboard model provides a high-level abstraction of knowledge and solution techniques for dynamic control and allows use of the knowledge for opportunistic and incremental problem solving. A number of systems have been developed and reported in the literature, where the blackboard model is used for structuring the problems and solving them [3]. A brief overview of blackboard architecture, a review of major developments which helped in evolution of the model, typical applications, a review of blackboard development shells, and steps involved in development of a major application are presented in this section. A typical example of the design of a plate girder is taken for illustration of the model.

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7.3.1 Blackboard Architecture

The three basic components of a blackboard system are knowledge sources, blackboard data structure and control. In the backboard model, knowledge required to solve a problem is decomposed into smaller independent knowledge sources. The knowledge sources can be represented using any of the knowledge representation schemes. Generally, the active problem-solving knowledge is represented in IF-THEN rules. Each rule set or knowledge source contains knowledge for resolving one task in a design process. Depending on the nature of the problem, frames, procedures and databases can also be used as and when required. The blackboard holds the global data and the information on problem-solving states. Activation of knowledge sources modifies the states in the blackboard leading to an incremental generation of the solution to the problem. Knowledge sources interact with each other only through the blackboard. The blackboard can be visualised as a collection of objects (frames) with slots for storing the solution as it gets generated in an incremental manner. The objects in the blackboard also store the status of the problem being solved and an agenda of events. The control decides issues such as what knowledge to apply, when to apply, which part of the blackboard is being currently addressed etc., depending on the status of the problem solving. The general architecture of the blackboard model is shown in Figure 7.3.

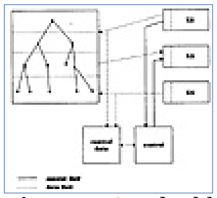

Figure 7.3 Blackboard model (KS = Knowledge Source)

As was mentioned earlier, the blackboard holds all the data objects. A hierarchical organisation is generally adopted for abstraction of these data objects resulting in two main advantages. (1) Knowledge sources are organised in such a way that they use information at one level as input and produce information for the next level. (2) The terminology associated with different concepts is made explicit and accessible at the appropriate levels of abstraction.

Since the problem-solving strategy is decomposed into a hierarchical organisation, the concept of event becomes predominant in blackboard-based problem solving. Any change in the blackboard is considered to be an event. Any change in the solution state either due to generation of additional information or modification of existing information is immediately recorded in the blackboard. The controller notes this change and takes necessary actions by invoking an appropriate knowledge source. This process repeats until the final solution for the problem is obtained. Another important point to be noted is that a subsequent change in information can make a previously taken decision false. In such cases, corresponding stages have to be undone by backtracking, leading to the reasoning to be non-monotonic. To carry out such backtracking, all the decisions made along with their dependencies have to be stored. The dependency network has to be built incrementally as the decisions are made using the knowledge sources. It not only helps in carrying out backtracking, but also helps in reviewing the progress of the problem-solving process.

7.3.2 Blackboard Framework

In a blackboard framework, the knowledge representation methods, techniques for scheduling knowledge, and partitioning of the solution space and the domain knowledge depend on the nature of the domain. The blackboard framework gives a description of the system components grounded on actual computational constructs and is a prescriptive model describing what goes into the blackboard. The problem to be solved is first decomposed into loosely coupled subtasks corresponding to the different specialised areas within the task. Functional decomposition of the tasks in a hierarchical manner allows common functions to be shared by many subsystems.

For development of an application, first the blackboard is hierarchically partitioned into objects defining the attributes of the solution space. The objects are connected through the links which can represent relationships between the objects. Such decomposition both at the knowledge level and at the blackboard level allows maximum flexibility during the development stage and the problem-solving phases. Such abstraction also reduces the computational needs by restricting the manipulations of smaller entities. After partitioning the solution space and the domain knowledge, the control information is added. In this framework, the blackboard serves as the structured working memory. Each knowledge source has a set of production rules and procedures and the control contains the strategy for application of the rules.

Details of implementation of the blackboard system are not attempted here, as there are many books and papers available on this topic [4–7]. A number of prototype applications were developed from as early as 1980, in different domains which contributed to the development of the model to the present state.

HEARSAY II, one of the earliest blackboard-based systems developed at Carnegie Melon University [8], was intended to answer queries about and retrieve documents from a collection of computer science abstracts in the area of AI, covering a selected vocabulary of around 1000 words. HASP/SIAP is another blackboard model-based system, which was used to develop and maintain a situation board that reflects the activities of the platforms (surface ships and submarines) in a region under surveillance [9]. Input to the system was a continuous stream of acoustic signals produced by objects in the region and intelligence reports containing information about movements of friendly and hostile platforms and routine commercial shipping activities. CRYSALIS, a system that determines the structures of proteins, given their animo acid sequence and X-ray diffraction data, for the first time introduced use of multiple hierarchies on the blackboard through panels [10]. Ong et al. [11] developed a mobile robot position estimator system based on the blackboard model for a robot with a limited sensory capability moving in a fixed environment, in which the details of the environment are suitably stored in the robot database. In this system, there are two blackboard panels, containing solution space details and control details. In both blackboard panels, the abstraction hierarchy labels are the same and only the attributes and values are different. The knowledge sources are classified as specialist and scheduling knowledge sources.

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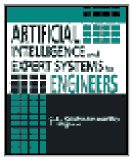

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DESTINY is a conceptual model for integrated structural design, proposed by Sriram [12]. In DESTINY, the blackboard is divided into levels depicting an a priori plan of the solution state with decomposition natural to the problem domain. The hypotheses in the blackboard are related through structural relationships. DESTINY has three levels of knowledge sources, viz., strategy level, specialist level and resource level. Strategy-level knowledge sources determine the course of the next action based on an analysis of the current solution state. Specialist knowledge sources contribute to solution generation in the blackboard, for example, knowledge for configuration generation, preliminary analysis, detailing consultant and critical evaluation of different designs from specialist knowledge sources. Resource knowledge sources contain the analytical knowledge and information on specification and codal provision.

GENESIS is a prototype system for planning and design of steel industrial structures proposed by Sakthivel and Kalyanaraman [13]. It is capable of performing engineering activities consisting of structural planning, preliminary design, analysis and detailed design of single-story steel industrial buildings in an integrated manner. Starting from any arbitrary plant layout and spatial constraints specified by the user, GENESIS develops the geometric layout of structural systems at different levels of abstraction and designs typical structural components in the layout. In GENESIS, geometric space contains objects describing the geometric attributes of every structural component or system in an industrial building. The design space is generated by selecting typical structural elements, possibly corresponding to more than one instance of the geometric space objects, for detailed design. Geometric and design space frame objects are stored in a frame library and instantiated whenever required through various knowledge sources on the respective solution blackboard partitions.

In GENESIS, the control events in the control blackboard are divided into meta events, planning events and design events. Meta events describe planning and design activities at a higher level of abstraction. Planning and design events describe specific subevents in the planning and design process. Different control knowledge events are used at different problem-solving stages to control the process of engineering of steel industrial structures. The functional knowledge sources are grouped into six knowledge modules, viz., structural planning knowledge module, design space generation knowledge module, preliminary design knowledge module, analysis knowledge module, detailed design knowledge module and design criticism knowledge module. Each knowledge module contains many knowledge sources to perform the engineering activities associated with different types of structural systems that can be adopted. The database is used to store static and dynamic data. The steel section properties of different rolled shapes, design tables such as standard crane data and numeric tables from governing codes such as wind pressure coefficients are stored in the static database. The schema for storing analysis results, nodal loads, design results, structural configurations etc. are provided at the time of knowledge base development and are used for storing these results at run time. The dynamic databases are specific to a problem. A schematic representation of GENESIS is shown in Figure 7.4.

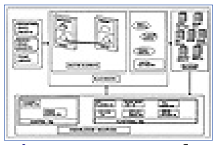
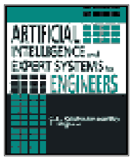


Figure 7.4 Architecture of GENESIS

Development of a number of blackboard models and prototypes has eventually led to general purpose blackboard shells. Most of these shells have been developed using the experience gained in developing prototype or application systems. For example, the experience with HASP and CRYSALIS led to a generalised blackboard system AGE (Attempts to GEneralise) at Stanford University. AGE permits the user to build blackboard systems in which attention is focused on a particular node of the blackboard object tree at any point of problem solving, and scheduling is done based on a set of priorities [14]. The main contribution of AGE has been in the design of subsequent general blackboard shells. HEARSAY III is the blackboard generalisation from the experience in the earlier projects HEARSAY I and II. The major contribution of this shell is a knowledge-based control procedure having a separate scheduling blackboard to make the control information visible and accessible to control knowledge sources. It has an integral context mechanism that allows simultaneous and alternative interpretations. BBI is the third generalisation in blackboard systems having a full-fledged separated blackboard architecture for controlling the execution of the domain knowledge sources [15]. It has graphical user interface for building knowledge bases, blackboards and knowledge sources.



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7.3.3 Integrated Engineering System

The integrated Engineering System (IES) is an extended blackboard framework proposed by Shaktivel and Kalyanaraman [16], which addresses the complex demands posed by engineering processes on the computing environment. The salient features of IES are:

- ability to handle a diversity of numeric, graphic and symbolic parameters;
- ability to use a variety of knowledge, methods and procedures efficiently;
- management of a large volume of static and dynamic data uniformly and efficiently;
- representation of the solution at various levels of abstraction starting from the most general to the most specific;
- ability to handle problems covering the entire range of the derivation-formation spectrum; and
- modelling and control of the cooperative process of engineering.

A schematic view of the IES architecture is presented in Figure 7.5. IES provides a framework in which a cooperative engineering process is modelled in an extended blackboard system. In IES, the blackboard is a common global data structure which serves as a communication medium between various independent knowledge sources. As the solution progresses, the schedule knowledge source posts a solution on the blackboard and also retrieves the necessary information posted by other knowledge sources for its problem solving. In IES, the blackboard is partitioned into solution blackboard and control blackboard panels. The solution blackboard panel stores the solution generated during the problem-solving process. The information is stored in objects along with their relations in a hierarchical form. The objects are instantiated in the solution blackboard at run time from the frame library which contains the objects and their attribute descriptions. The relational links between the objects in the solution blackboard are created through knowledge sources. In addition to storage of values, a limited amount of reasoning can be done in the objects through multiple inheritances as well as demons. Knowledge sources can also be invoked through the demons.

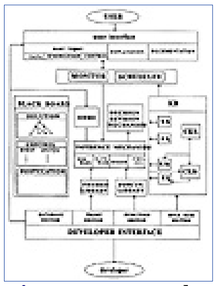

Figure 7.5 Architecture of IES

The control blackboard stores the status of control events as the solution progresses. Control events describe the problem state in the most abstract form. For instance, an event *analysis* can have different states (status) such as ‘cannot be started’, ‘can be started’, and ‘completed’. At run time, the instance-specific control events are generated dynamically depending on the number of instantiations of the object on the solution blackboard in which the control event is focused. The status of the control events are modified by the knowledge sources, as the solution progresses. The control event status information is used by the knowledge source selector to invoke an appropriate knowledge source at any given problem state. In IES, the knowledge sources are functionally classified into three categories, viz., control knowledge sources, functional knowledge sources and task-specific knowledge sources. Based on the inference process, knowledge sources are classified as autonomous knowledge sources, interacting knowledge sources and coordinating knowledge sources. Autonomous knowledge sources work independently and model the infrequent interaction during cooperating problem solving by different experts by allowing communication between the different knowledge sources only through the blackboard. Interacting knowledge sources are used to represent knowledge in coupled subtasks. IES allows knowledge to be represented in each knowledge source in its own language and no constraint is placed on the syntax and semantics used by the different knowledge sources. The coordination between various interacting knowledge sources is achieved through mapping provided in a coordinating knowledge source. Whenever a coordinating knowledge source is invoked, the reasoner takes the coordinating knowledge source as the common objective of the set of interacting and independent knowledge sources specified in the coordinating knowledge source and tries to achieve the goal with the help of knowledge available in those sets of knowledge sources. IES provides four reasoning mechanisms, viz., forward, backward, hybrid and fire-all techniques. Different reasoning strategies can be used in different knowledge sources.

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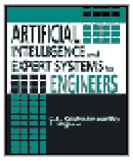

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7.3.4 Illustrative Example

To get a better insight into the problem solving based on blackboard model, a simple problem of Design of Plate Girder is taken up. The details of formulation and implementation using IES are presented below. As all the variable and control event names are self-explanatory, detailed descriptions are not given. The following control events are identified for the problem.

1. User Input
2. Load Estimation
3. Web Design
4. Flange Modelling
5. Flange Design
6. Stiffener Design
7. Output

The system has ten knowledge sources, and the salient features of the knowledge sources are briefly described below. A typical knowledge source has the following sections.

default goal	termination criteria of the knowledge source
precondition	describes the status of control events for the knowledge source to get activated
knowledge source type	whether knowledge source is independent, interacting or coordinating type
inference strategy	inference strategy to be used for the knowledge source
rules	knowledge in the form of rules rules can interact with objects in the blackboard

To have a better understanding of blackboard-based problem solving, the status of control events and actions taken at different stages for the problem under consideration are presented below. At the beginning of problem solving, the status of control events is as shown below.

User Input	not completed

Load Estimation	not completed
Web Design	not completed
Flange Modelling	not completed
Flange Design	not completed
Stiffener Design	not completed
Output	not completed

The knowledge source for input is invoked which in turn invokes a procedure to get the required input from the user. At the end of execution of the knowledge source the status of control event *User Input* is set to 'completed' and the status of *Load Estimation* set to 'can be started' as shown below.

User Input	completed
Load Estimation	can be started
Web Design	not completed
Flange Modelling	not completed
Flange Design	not completed
Stiffener Design	not completed
Output	not completed

The knowledge source for load estimation is invoked at this stage. The controller of the blackboard system identifies the appropriate knowledge source by checking the preconditions given in the knowledge sources. For instance, the precondition in the load estimation knowledge source is as given below

```
IF      status of control event User Input IS completed
AND     status of control event Load Estimation IS
        can be started
```

The controller of the blackboard monitors the status of the control events and the preconditions of the knowledge sources, and invokes the appropriate knowledge source. The knowledge source in turn modifies the status of the control events in the blackboard. The process continues until, the status of all the events becomes 'completed'. In the process of problem solving, conflicts can arise, in case more than one knowledge source tries to establish a value for the same variable. Such situations are indicated in the blackboard. Appropriate knowledge sources are invoked at this time for conflict resolution, if such a situation arises.

Parallel and distributed processing can be introduced at different levels in the blackboard paradigm. A semantic synchronisation of blackboard data is required for effective parallelisation of the blackboard model. Attempts have been made by researchers in the past to parallelise the blackboard model for specific problems. Corkill has proposed a model for concurrent execution of knowledge source instances, wherein a multithread execution of knowledge sources is carried out based on a predefined priority rating [17]. Rice et al. [18] proposed two models, (1) a blackboard framework designed to operate on distributed-memory multiprocessors and (2) a blackboard framework to operate on shared-memory models. They reported considerable speedup, as a 0result of distributed implementation of blackboard model [18].

Object-oriented blackboard architecture for model-based diagnostic reasoning proposed by Buttner et al. is an improved scheduling of knowledge source activation, where a strategy knowledge source orders the triggered knowledge sources before they are actually activated [19]. A number of researchers are still continuing work to evolve object-oriented blackboard models to operate on machines with multiprocessors.

7.4 ODESSY - An Integrated System for Preliminary Design of Reinforced Concrete Multistory Office Buildings

Building design is a very complex engineering activity involving the cooperative participation of multiple specialists representing disparate domains like architectural, structural, construction, HVAC (Heating, Ventilation and Air-Conditioning) etc. In practice, the building industry is characterised by *fragmentation* among the various phases of the design process, like layout planning, conceptual design, preliminary design, analysis, detailed design and construction [20]. Interaction and feedback among the participants that are so essential to the generation of globally acceptable designs are either inadequate or occur too late in the design process. This often results in suboptimal designs that might entail costly rework, thus causing unforeseen delays in the execution of the project. Design integration is seen as the means by which the coordination concerns in the building industry can be addressed. Recent attempts to develop integrated computer systems for design have indicated that KBSs can serve as vehicles for promoting integration, both vertically across the many phases of planning and design and horizontally across the many subdisciplines involved [21–23]. In the following subsections, a process model that has been proposed and used [24,25] to address the tasks involved in the integrated design of multistory office buildings is explained.

7.4.1 Task Analysis of Building Design

Based on a study of the design process as performed by a set of experienced designers solving building design problems, the following issues have been identified as central to integrated building design.

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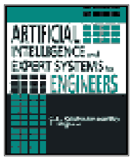

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Multidisciplinary nature of problem-solving knowledge

Many disparate knowledge sources contribute to the evolution of a building design. Their individual contributions might often come into conflict with each other. Therefore, a globally acceptable solution usually represents a compromise among the knowledge sources whose preferred local solutions are not fully compatible.

Existence of multiple solution paths

The preliminary stages of building design are characterised by the existence of multiple solutions. Each solution path needs to be pursued till such time as it is proved to be decidedly inferior to its alternatives. Issues concerning multiple solution generation include knowledge representation for generation and efficient constraint application strategies for early pruning of infeasible paths.

Qualitative nature of evaluation

In the preliminary stages of design, the nature of evaluation is qualitative and is expressed in imprecise, linguistic form. Hence decision support tools that can handle knowledge in imprecise, qualitative form are needed to perform evaluation.

Need to enforce consistency

An offshoot of the multiagent nature of the building design domain is that decisions have to be made and revised during reasoning. This affects the integrity of the solution. Hence, strategies need to be specially devised to enforce consistency of the solution during the reasoning process.

Horizontal and vertical integration

The multiphase, multiagent nature of the building design task necessitates integration, both vertically across the many phases of the design process and horizontally over the disciplines affecting the design.

7.4.2 Synthesis-Criticism-Modification Model

The first step towards arriving at an integrated solution for building design is to evolve a process model for building design that addresses all the issues discussed above. An examination of the process models reported by the researchers [26–28] shows that the existing models do not satisfactorily address all the issues identified above.

A process model, called the Synthesis-Criticism-Modification (SCM) model, proposed recently [25] views building design as consisting of multiple phases of a three-step process of synthesis, criticism and modification. The scope of the model is limited to two phases, viz., layout planning and conceptual and preliminary design of reinforced concrete multistory office buildings. In each phase, the synthesis step generates multiple solutions. Each of these solutions is then critiqued from the viewpoint of every participating knowledge source. In the final step, one or a few highly rated solutions are modified, if necessary, based on the feedback provided by the critics. Figure 7.6 shows the architecture of the SCM process in a typical phase of design. The knowledge representation schemes and inference strategies for each of the components are briefly described below.

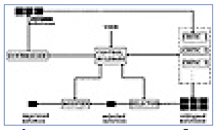
Figure 7.6 Architecture of the SCM process

Design Synthesis

In Chapter 4, the concept of design synthesis and the decomposition model used in the synthesis process have been explained in detail. This model is found to be most suitable for the synthesis step of the proposed model because (i) the building domain lends itself easily to hierarchical decomposition and (ii) the model facilitates multiple solution generation. GENSYNT described in Chapter 4 is used for developing the synthesisers that form part of the integrated system. The decomposition representation of the layout of the building, which is used in the first phase, viz., layout planning, is shown in Figure 7.7.

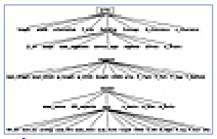
Figure 7.7 Decomposition tree for layout synthesis

Design Critiquing

Design synthesis ensures that every generated solution is feasible. Since building design is a multiagent process, it is inevitable that each solution will meet the local preferences of each participating agent with varying degrees of satisfaction. Design critiquing, explained in Chapter 5, is the process of evaluating a solution to determine its *desirability*. It also creates a feedback loop of information that can be used to improve the solution. In a multiagent design context, critiquing will have to be done by each agent participating in the solution-building process.

During the knowledge elicitation stage, it has been observed that at the preliminary design stage, preferences are stated in a qualitative manner. The Fuzzy Weighted Averaging (FWA) technique provides a rational means to evaluate solutions based on such qualitative criteria [29–31].

A fuzzy-based model has been proposed for design critiquing [25]. The highlights of the model are (i) a *taxonomy* for aspects to be critiqued based on the complexity of attribute interaction involved in the assessment (the hierarchical tree used in GENCRIT is adopted for this purpose), (ii) a formalism for representing critiquing knowledge that enables assigning of *fuzzy linguistic ratings and weights* for evaluated aspects, (iii) membership functions for internal representation of fuzzy linguistic variable values, (iv) a *FWA* process for generating overall solution ratings, (v) a *Ranking Index* (RI) scheme for ranking solutions and (vi) generation of both *user-readable and machine-readable critiques* that justify the fuzzy rating and provide specific suggestions for improving the solution.

A domain-independent generic tool for performing design critiquing, called FUZCRIT (FUZzy CRItiquing Tool) has been developed that aids in rapid development of critics [25]. The architecture of FUZCRIT is shown in Figure 7.8.

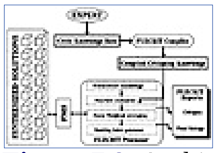

Figure 7.8 Architecture of FUZCRIT

Design Modification

In an automated environment, the system itself has to respond to the critiques made by the participating agents to effect any possible improvement to the solution. This step is termed modification. Modification is a knowledge-intensive task, depending largely on the expertise available to make decisions. Design modification poses two major problems: (i) Conflicts may arise between the suggestions made by the various critics and these have to be resolved before effecting a modification. (ii) Design modification entails revision of decisions already made, thus affecting the consistency of the solution. Hence, whenever a modification is to be made to the solution, measures have to be initiated to preserve the consistency of the solution.

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The design modification model

A model for design modification that addresses the two issues stated above has been proposed and developed [25]. The input to the modifier consists of the solution to be modified and the set of critiques generated by the critics that have evaluated the solution. For the modifier to respond to the critiques made by various critics, the critiques have to be very specific. A template that has been proposed for representing critiques is shown in Figure 7.9.

Figure 7.9 Template for representation of machine-readable critique

Every critic that evaluates a solution posts its critiques into a *modifier table* in the global space. A *multilevel priority specification strategy* has been proposed to resolve conflicts among critiques in the modifier table. Following the resolution of all conflicts, the final resolved set of critiques is posted on to an *execute table* which is then used by the modifier to trigger changes to the solution.

Since considerable dependencies exist between the attributes of a solution, consequences of a change to an attribute of the solution can be extensive. A *revision-propagation mechanism* that has been proposed in the thesis enables the consequences of a change to a solution attribute to be propagated to the appropriate extent automatically.

The KBS Development Tool

The SCM-based process model has been implemented using DEKBASE and two generic tools GENSYNT and FUZCRIT. The application of the SCM model to the two identified phases of the preliminary building design process are described below.

7.4.3 Layout Planning

Layout planning forms the first phase of the conceptual design of a building, wherein the allocation of space for the various functions of the building is performed taking into account multidisciplinary criteria. This phase of the design is characterised by the existence of a potentially large number of alternatives, and a systematic and computationally efficient methodology is needed to enumerate all the feasible solutions. Since the space within the building has to cater to a variety of functions like architectural, structural and building services, a broad spectrum of concerns has to be taken into account while evaluating the relative merits and demerits of the generated solutions [32,33].

The layout planner consists of a controller, a layout synthesiser and three critics representing the architectural, structural and service domains. The controller, among other things, sets up the context for the synthesiser and critics, and invokes them at appropriate stages of the layout-planning process. The domain knowledge itself is organised in the synthesiser and critics.

Before describing the layout-planning approach, it is worthwhile to examine a generalised building layout alternative in terms of the parameters to be generated and the relations between these parameters which need to be satisfied. A generalised building layout alternative is shown in Figure 7.10. The basic geometric parameters are marked in the figure.

Figure 7.10 Basic geometric parameters of a building layout
(a) elevation (b) plan

In Figure 7.10, H - Height of building, L - length of plot, W -width of plot, 1_1,1_2 - length of segment1 and segment2, respectively, and w_1, w_2 - width of segment1 and segment2, respectively.

The Layout Synthesiser

The layout synthesiser is a generative system that contains the knowledge required to generate feasible solutions. The major decisions made during layout planning are the shape and dimensions of the building outline, the number of floors in the building and the location and size of the service core [34]. The decomposition of the building for layout synthesis is shown in Figure 7.7.

The *prototype refinement paradigm* [35] has been used to generate the layout plan. The synthesiser starts with various generic prototypes and uses problem-specific information and constraints to generate the layout scheme. Some of the generic prototypes supported are shown in Figure 7.11.

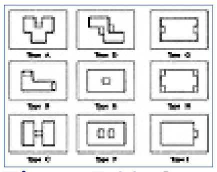

Figure 7.11 Generic building prototypes for layout planning

The Layout Critics

Building design is a cooperative process with the architect, structural engineer and services specialist playing prominent roles. The three critics representing these three domains bring their respective viewpoints to bear on the generated solutions. Critic rules assign fuzzy ratings and weights to the various aspects being critiqued. The FWA process is then applied to determine the overall worth of the solution.

At the layout-planning phase the modification step is not invoked. This is because the design space at the layout-planning stage is a discrete space and the synthesiser does an exhaustive search of this space. Hence any modification to any of the generated solutions can only lead to another solution that has already been synthesised. Hence, following the critiquing step, one or a few of the highly ranked solutions are directly selected for the next stage of the design.

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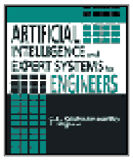

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7.4.4 Conceptual and Preliminary Design

The second phase of the building design process concerns the conceptual and preliminary design of the building.

Ideally, the conceptual and preliminary design module should be able to take in an arbitrary complex building plan, formed with orthogonal boundary lines and having one or more service cores located anywhere in the building plan, as input and be able to generate and evaluate a wide range of alternatives both from cost considerations as well as from less precise and more qualitative viewpoints like constructibility. The selected solution should then respond to criticism, if necessary, and modify such of its aspects as are evaluated by the critics as less desirable from an overall project viewpoint. Existing KBSs for this phase of design do not adequately address these requirements [36–39].

Unlike in the layout-planning stage, the design space at this stage is more densely populated and an explicit generation and evaluation of all these alternatives is practically infeasible. Besides, the identification of cost as one of the major criteria in arriving at a satisfactory preliminary design solution points to the use of optimisation techniques for generating the solution. However, at this stage of design, when the form of the solution itself is unknown, the formulation of design as an optimisation problem presents several difficulties. Also, qualitative considerations like constructibility, that fall outside the purview of optimisation, also need to be incorporated in the evaluation process.

Obviously, neither decomposition-based synthesis nor optimisation techniques by themselves can handle this phase of design. Hence, a hybrid approach in which the two complement each other’s strengths has been proposed.

In this approach, the structural *framing generation* task is handled by a combination of heuristic and optimisation techniques while the task of *selecting and configuring the structural systems* for the chosen framing plan is performed by the synthesiser.

Zonal Decomposition of the Building Plan

Framing plan generation is accomplished by first generating sets of *column lines* in orthogonal directions and then locating the columns at the intersection of these lines. For this purpose, the complex building plan is decomposed into several rectangular *zones* in either direction. The zones are classified as either *free* or *constrained* zones depending on whether or not they contain elements that constrain the placement of columns within them (Figure 7.12). In the building plan shown in the figure, Zone 4 in the transverse direction and Zone 3 in the longitudinal direction are *constrained* zones, while the remaining are *free* zones.

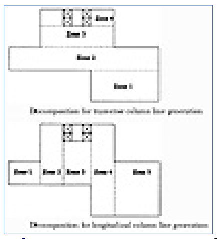


Figure 7.12 Zonal decomposition for column line generation

While heuristic techniques are used to generate the framing plan within constrained zones, unconstrained optimisation techniques perform framing plan generation in the free zones.

The GA Model for Structural Framing Generation

Based on the characteristics of the problem and the capabilities of various optimisation strategies, the GA [40] has been adopted for performing the optimisation. The optimisation variables are the number and location of the column lines in the two orthogonal directions. The complexity in modelling this problem arises because the number of column lines itself is dynamically determined. A proposed novel *genetic coding scheme* in conjunction with the *zonal decomposition* technique enables modelling of the problem for GA-based search [25].

The Decomposition Model for Conceptual and Preliminary Design

The decomposition model performs structural system configuration for the generated framing plans. The synthesiser is capable of generating up to four different flooring system alternatives for a given framing plan depending on the constraints. The four different flooring systems considered are shown in Figure 7.13.

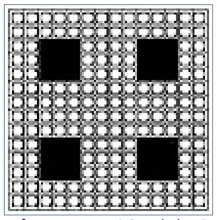


Figure 7.13 (a) A typical waffle slab floor

For each framing plan that is input to it, the synthesiser returns the least-cost structural system alternative to the framing plan generator. A schematic view of the interaction between the optimisation and synthesis modules in the solution generation process is shown in Figure 7.14

The hybrid GA-decomposition process is illustrated below for a typically complex building. The plan of the building outline is shown in Figure 7.15

The least-cost solution is shown in Figure 7.16. In all, there are *twelve* bays in the longer direction and *nine* along the shorter direction. The floor system for the building is a *beam and slab* system.

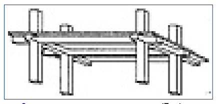


Figure 7.13 (b) Typical beam and slab floor

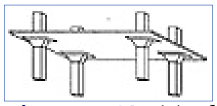


Figure 7.13 (c) Flat slab floor

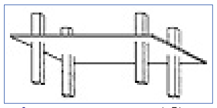


Figure 7.13 (d) Typical flat plate floor

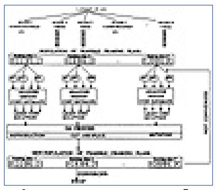


Figure 7.14 Schematic view of the hybrid GA-decomposition process

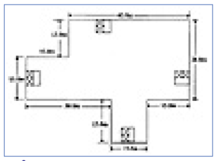


Figure 7.15 Input layout plan

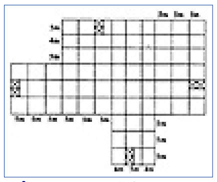


Figure 7.16 Least-cost framing plan

The Preliminary Design Critic

The least-cost alternative generated through the hybrid approach is subjected to criticism from both constructibility and architectural viewpoints. Various aspects affecting the constructibility and architectural expressiveness of the design have been formalised and represented in the critic.

The Design Modifier

The modifier attempts to improve the critiqued solution by incorporating the critiques posted on the modification table. The tradeoff that is required, in terms of cost, to convert a least-cost alternative (the one generated by the optimiser) to a more constructible and architecturally expressive solution (the same solution after criticism and modification) is presented to the user.

7.4.5 Architecture of ODESSY

The integrated prototype system called ODESSY (Office Building DESign System) has been developed using the SCM model [25]. The architecture of the system is shown in Figure 7.17. As seen in the figure, the ODESSY controller facilitates two points of entry into the system and thus can either be used to perform one of the two individual tasks, viz., layout planning and conceptual and preliminary design, or to perform the entire preliminary design process. Information relating to the current status of problem solving in ODESSY is held in global variables. Frame bases hold solution information that is to be shared by various modules.

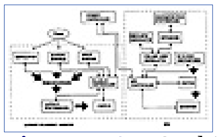
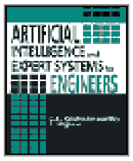


Figure 7.17 Architecture of ODDESSY



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7.5 Conceptual Design of a Car Body Shape

Conceptual design of car body shape is a typical problem in which many of the concepts discussed in earlier chapters are used. The problem involves use of both mathematical constraints and heuristics. This section presents an illustration of an integrated approach to an application development using tools such as design synthesis, criticism and case-based reasoning. The size of the problem is sufficiently large and several of the requirements are conflicting in nature. The problem also provides sufficient scope for subjective evaluation.

7.5.1 Functional Requirements

The functional requirements of the conceptual design of a car body shape are defined as the minimum set of independent requirements that completely satisfy the design objectives for a specific need and are described below [41–45].

Stability	Directional stability is the tendency of a car to maintain its existing course. This requires a high positive pitch moment, implying low front lift and high rear lift.
Response	This is a measure of ability of the car to respond to changes in its direction. For better response, the front lift should be high and the rear lift low resulting in low positive pitch moment.
Maintenance	This refers to the mud deposition on the body of the car.
Entry and Exit	This refers to the ease with which entry into the car may be effected.
Drag	This is the aerodynamic drag experienced by the car body because of its shape.
Visibility	This is the ease with which a person inside the car may view the road ahead.
Ventilation	High ventilation indicates that there is proper ventilation of air inside the car.
Volume Effectiveness	This indicates the ratio of the interior volume of the car to the three-dimensional parking volume of the car.
Aesthetics	This refers to the beauty of the car and is a highly subjective requirement.

The objective of the exercise is to obtain the best solution with respect to the above functional requirements.

7.5.2 Design Parameters

After a detailed study of the design process of automobile bodies, the following design parameters are identified. Design parameters are defined as the key variables that characterise the physical entity created by the design process to fulfil the functional requirements. The design parameters are shown in Figure 7.18.

- Grille area length
- Grille area inclination
- Cowl length
- Cowl angle
- Windscreen length
- Windscreen inclination
- Roof length
- Rear angle
- Boot length
- Underclearance
- Side height (till tumblehome inclination)
- Tumblehome inclination
- Breadth

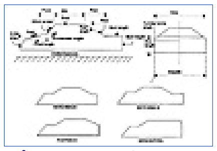
Figure 7.18 Design parameters considered for car body shape

Out of the nine functional requirements stated above, only five features, viz., front lift, rear lift, maintenance, entry and exit, and drag, are considered for generating the solutions by the synthesis process. The solutions obtained are evaluated/critiqued for the remaining functional requirements later.

The 13 design parameters are grouped into five major categories which are in accordance with the design axiom. The groups are:

1.	Front	This includes grille area length, grille area inclination, cowl angle, cowl length, windscreen length and windscreen inclination
2.	Mid	This includes roof length
3.	Rear	This includes rear angle, boot length and boot height
4.	Side	This includes side height, tumblehome inclination and breadth
5.	Underclearance	

For simplicity, the car body was assumed to consist strictly of straight edges.

7.5.3 Design Decoupling

Once the functional requirements and design parameters are identified, design decoupling is done to make the functional requirements independent of each other. The axiomatic approach proposed by Suh [46] provides a mechanism for controlling the functional requirements independently. This can overcome difficulties such as dependency-related modification of the design parameters leading to a large number of iterations. Hence, it is possible to obtain a decoupled design matrix to ensure the independent control of functional requirements.

Design decoupling generates a decoupled design matrix, which exhibits the characteristics of the design problem. The design problem is represented in the form of an equation involving the design matrix [A], which relates the functional requirements [FR] and design parameters [DP] as shown below:

$$[FR] = [A]\,[DP]$$

According to the axiom proposed by Suh, in an acceptable design, the design parameters and functional requirements are related in such a way that specific design parameters can be adjusted to satisfy the corresponding functional requirements without affecting the other functional requirements. For this, the matrix [A] has to be decoupled. A design is said to be uncoupled, when the functional requirements are independent of each other, and is represented by a diagonal matrix. A lower or upper triangular matrix represents a decoupled design. FR_i is dependent only on DP_i in an uncoupled design. Since such situation does not occur in large engineering design problems, off diagonal elements do exist in [A].

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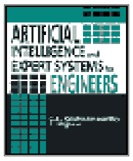

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Algorithm for Decoupling

1. Shuffle the rows and columns of matrix [A] to determine whether it is already a shuffled lower triangular matrix, in which case it is already decoupled.

2. If the matrix is not already decoupled, then all possible permutations of rows and columns are generated and the matrices corresponding to every permutation of the rows and columns are created. For any such matrix, if a single diagonal element takes a value zero, that matrix is rejected. For matrices that are not rejected, this step returns all the non-zero elements in the upper triangular part of the matrix.

3. The solutions returned from the above step are inspected for overlapping, in the sense that a solution which is a subset of another solution is considered to be superior and the matrix corresponding to the superset solution is abandoned.

This algorithm finally returns the row and column numbers of the elements that have to be forced to zero for decoupling. All the elements which have to be forced to zero form the solution set. It may be noted that the algorithm for design decoupling is approximately of order factorial *n*. This is because all the possible permutations of the rows and columns have to be considered.

The first step in design decoupling.is generation of a design matrix. It is done after a detailed study of the dependency of the functional requirements on each design parameter. A brief description of the dependencies is presented below.

Front lift	The front lift of the car depends on grille area length, grille area inclination, cowl length, cowl angle, windscreen length and windscreen inclination. The front lift is due to the flow of air over the front of the car. This creates a region of low pressure, resulting in lift. Also, the higher the vorticity of the flow, the lower is the pressure.
Rear lift	Rear lift depends on the design parameters of the rear and the side. The dependency on the rear is due to the flow velocity and vortex as explained in the front lift. The dependency on the side is due to the fact that the wake structure, which varies with the type of the car (and depends on predominantly tumblehome angle), affects the rear lift. As long as the air flow over the roof gets reattached on the trailing edge of the boot, the rear lift constantly goes down with reduced rear angles. A similar explanation is applicable to the effects of boot length elongation on rear lift.

Maintenance	Maintenance is a function of the rear and the underclearance. The air flowing into the underclearance of the car picks up mud and dirt from the road. The air entering into the front of the underclearance is not equal to the air leaving from the rear of the underclearance. This occurs due to the pressure drop in the flow from the front to the rear of the underclearance. Hence, there will be some flow from the side of the underclearance to account for continuity. The flow leaving the underclearance from the side and the rear moves up to hit the body of the car. The shape of the rear of the car is a significant determinant of the type of the rear wake. The type of rear wake determines the amount of flow out of the rear of underclearance which hits the rear walls of the car body, thus controlling the mud deposition (maintenance) on the rear of the car.
Entry and Exit	Entry and exit depends on front, mid, rear and side. Whenever data is not available on any functional requirement it is assumed to be dependent on all the functional requirements. However, the under clearance dependency has been left out, because it is difficult to envisage a car in which the entry and exit is through the underclearance. Also it is assumed that entry and exit through any other position of the car is independent of the value taken by the design parameter underclearance.
Drag	Drag is a function of all five of the design parameters, the front, mid, rear, side and the underclearance. The air flowing over the car causes drag due to the effect of viscous friction. Hence, all parts of the car contribute to the drag. The velocity and vorticity of the flow are predominant characteristics of the flow which affect the drag. The vorticity of the flow depends on the design parameters in some cases, such as side, because the type of flow depends on the design parameters explained in rear lift.

Decoupling of the design matrix led to 25 design solutions. In essence, the functional requirements have been rendered independent of each other and the solution characteristics of such a design have been determined. Now the designs are synthesised subject to these characteristics. The first solution of decoupling is {(2,4),(4,4)}. (2,4) indicates that the rear lift must be independent of the side and (4,4) indicates that the entry-exit must be independent of the side. This constraint was imposed during synthesis. The decomposition tree for the problem for carrying out synthesis is shown in Figures 7.19 to 7.23. The decoupling requirements are satisfied by enforcing the following conditions. First, the vortex at the side of the car is made to zero. Secondly, the door position is set at mid, hinging it along the length of the car and by keeping the length of the door in the perpendicular direction to the hinge (breadth) not equal to the breadth of the car. This setting ensured prevention of the air from flowing over the side of the car, thus achieving the decoupling. Preventing air flow over the side results in an increase of air flow over other parts of the car. This may have secondary effects. The net effect on the car is a result of all these effects and is, therefore, determined through an evaluation process.

7.5.4 Synthesis and Critiquing of Solutions

The solutions generated by the synthesiser were evaluated for all the functional requirements; except aesthetics. Aesthetics is not included because it cannot be rated by methods adopted for any of the other functional requirements. Only 120 solutions out of many thousands possible are generated and evaluated.

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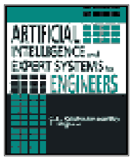

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7.5.5 Case-Based Evaluation of Shapes

Aesthetic evaluation of car bodies is very much a subjective process. The rating obtained after aesthetic evaluation by a designer is usually based on his own taste and the market forces. This rules out any standard evaluation procedure which would be guided by the shapes of existing cars in the market. Case-based evaluation using the CASETOOL described in Chapter 6 was used for carrying out evaluation for aesthetics.

Each of the existing cases is stored in the knowledge base as a case card. Comparison of the present case obtained after synthesis with the past cases from the case base is done based on different ratios. These ratios indicate the proportions of the dimensions of the car body. Five cases of each of the four types of car shapes (fastback, notchback, hatchback and wagontype) are selected from the available data [41], and the cases were stored in the case card along with the knowledge of the type of the car.

The ratios identified were used for determining the relevance of the present case with the stored cases. For each of the five cases, the ratios for the current case are compared with those from the stored cases, and the relevance norm is computed. The case with the lowest value of relevance norm is taken as the most acceptable form from the aesthetic point of view.

7.6 SETHU - An Integrated KBES for Concrete Road Bridge Design

Early researchers in the field of bridges [47–51] treated the preliminary stages of the bridge design process as consisting of heuristic knowledge which was expressed in the form of production rules. However, the bridge design process is characterised by the involvement of complex knowledge which cannot be represented using production rules alone. A more comprehensive work has been carried out to identify these complexities and address the preliminary design stages of the bridge design process [52]. Based on this work, which adequately addresses the issues of complex bridge design knowledge representations, a process model has been developed using appropriate AI-based methodologies. In the following subsections the methodologies adopted in the process model and the SETHU system are briefly described.

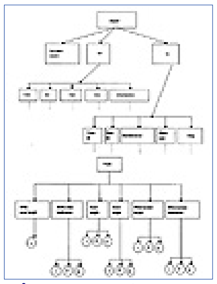
Figure 7.19 Decomposition tree - I

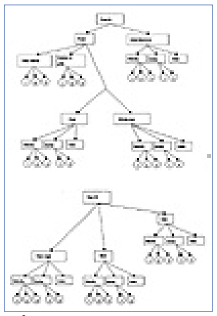
Figure 7.20 Decomposition tree - II

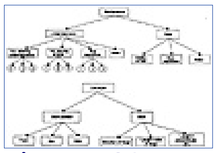
Figure 7.21 Decomposition tree - III

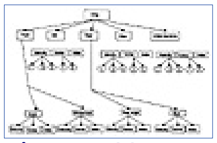
Figure 7.22 Decomposition tree - IV

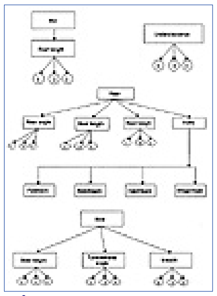
Figure 7.23 Decomposition tree - V

7.6.1 Task Analysis of Bridge Design Process

In actual practice, the bridge design process is carried out in two different ways. When presented with a new problem, the bridge design experts first try to recall a similar problem that has been solved before. In case the experts fail to recall a similar case, they build the solution systematically from scratch using their generalised knowledge of the domain. This approach involves exploring all the possible alternatives at every intermediate stage of the solution generation process. It is called the *heuristics-based approach*. If they do recall a similar past case, they adapt it to suit the new requirements. This is called the *case-based approach*, and in AI parlance it falls in the realm of problem solving by case-based reasoning, explained in Chapter 6. In the following sections, a task analysis of the preliminary design process, as approached by the two different strategies introduced above, is presented with a view to identify various complex knowledge forms and to abstract a model of the design process.

Heuristic-Based Approach

Site selection

During the site selection stage, alternate bridge construction sites are chosen based on field and laboratory tests. These sites are evaluated from economy and serviceability criteria to eliminate inferior ones. Various aspects such as total length, alignments, geological conditions, construction facilities and hydraulic aspects that govern the serviceability and economy of a site are used to evaluate the alternate sites. For this purpose, these aspects are classified into various categories. This categorisation facilitates evaluation of the desirability of the site from these individual viewpoints. An overall rating for the site is then arrived at based on the relative importance associated with each individually critiqued aspect. It was found that the knowledge for classifying the site data into categories for critical evaluation can be efficiently represented and processed using *production rule-based techniques*, and the critical evaluation of sites requires a *critiquing technique* that evaluates various individual aspects of a site and arrives at an overall rating on the basis of their relative importance [53].

Bridge layout planning

At the selected site, a layout (location of piers/arrangements of spans shown in Figure 7.24) is decided which satisfies the economy, clearance, hydraulic and geotechnical requirements. This process can be visualised as an interaction between four design experts, viz., layout planner, traffic engineer, hydraulic expert and foundation expert. Hence, bridge layout planning involves multidisciplinary efforts to find a satisfactory solution. Therefore, constraint-satisfaction techniques that enable modelling of such multidisciplinary processes are suitable for this task. The layout-planning knowledge can be represented as production rules and the clearance, hydraulic and geotechnical requirements can be represented as constraints. The reasoning process is non-monotonic and backtracking is necessary to maintain solution consistency. Therefore, a *rule-based technique for layout planning with dependency-based backtracking* and *constraint posting for solution consistency* are appropriate problem-solving techniques.

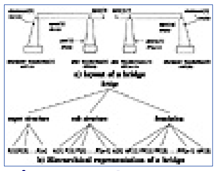

Figure 7.24 Representation of bridge structure

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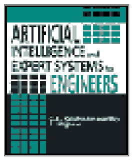

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Conceptual design of structural systems

In this step, various feasible structural systems are proposed for a given bridge layout and the inferior ones are eliminated based on a critical evaluation of the candidates from the viewpoints of economy, aesthetics, constructibility, etc. The bridge structure can be viewed as a hierarchical network consisting of various components and subcomponents as its nodes, as shown in Figure 7.24. Each component will in turn have various attributes whose values are to be determined and each of these attributes can take various possible values for a given situation. The decomposition tree for the conceptual design of bridge structural systems is shown in Figure 7.25. Decomposition-based representation of designs enables easy generation of all feasible candidates. Feasibility is ensured by eliminating incompatible assemblages through the application of constraints. This process of solution generation is termed *synthesis* and is explained in Chapter 4. Synthesising solutions using the decomposition tree requires a set of *preconditions*, which represent the context. These preconditions can be generated dynamically through a rule base. Therefore, for this stage, *rule-based inference* (to generate preconditions), (decomposition and constraint-based) *synthesis*, and *critical evaluation* (that critiques various individual aspects of a conceptual design and arrives at an overall rating on the basis of their relative importance) are appropriate problem-solving techniques.

Preliminary dimensioning of structural components

Using heuristics gained through years of design practice, design experts arrive at preliminary dimensions of the structural components of the chosen structural systems. These heuristics can be represented as production rules. The preliminary dimensions thus arrived at are used to compute the gross weight of the structures which can then be compared to determine the relatively lightweight alternatives. Therefore, for this stage, production rule-based preliminary dimensioning and comparative critiquing are appropriate.

Case-Based Approach

Site selection

In the case-based approach, similar past episodes of site selection are recalled from records and the criteria used on that occasion for selection or elimination of sites are ascertained. Potential sites are short-listed by directly applying these criteria. At this stage, experts also tend to look ahead at the later decisions that were made in the matching cases, to anticipate if the emerging solution may turn out to be undesirable.

Bridge layout planning

Those past sites that have their cross-sectional properties and other requirements similar to those of the current problem are retrieved from past records. Matching layouts are then chosen after examining the implication of adopting each of these as was done in the case of site selection. The chosen layout is then adapted suitably to meet the requirements of the current problem.

Conceptual design of structural systems

Cases are recalled on the basis of some crucial problem data with a bias towards those with relatively less weight and then adapted to suit the present situation. In case no complete design matches with the given situation, the conceptual design problem is addressed by the case-based design process on a component-by-component basis and care is taken to ensure that the components so selected can be assembled together without violating constraints governing their assemblage.

Figure 7.25 Decomposition tree for the conceptual bridge structural system

Preliminary dimensioning of the structural components

In the case-based approach, conceptual design and preliminary dimensioning are in fact accomplished simultaneously. The preliminary dimensions of the chosen structural system are simultaneously adapted to suit the current problem requirements.

The case-based approach relies completely on the ability of the system to retrieve similar past cases that help in problem solving. *Case indexing* is the most commonly used means of case retrieval and it is explained in detail in Chapter 6. A case index reflects the most distinguishing features of a case which happen to be qualitative in nature. In addition, bridge design cases are also characterised by various quantitative features that are important for case retrieval. The relevance of a past case to a given current situation varies based on the significance of each of these quantitative features. For such situations, case indexing alone is not sufficient for efficient case retrieval. Hence, in addition to index-based retrieval, the case-based bridge design also requires *actual value and relative importance based retrieval*. To avoid past mistakes a *facility for detecting the problems* associated with the past cases is needed. Since engineering design cases are large in size and cumbersome to handle, a *facility to focus on the relevant parts* to consider only a small portion of a past case is essential for building a solution using past cases. As past cases cannot be directly mapped to the current situation, a *facility for adapting* the past cases to suit the current situation is called for. Also, as the new solution can be built on a component-by-component basis by adapting parts of various retrieved cases, the adaptation should be done such that the resulting assemblage is compatible. A *facility for solution evaluation* is required to test its quality. Finally, if the case is found worthwhile, it needs to be stored in the case base. This also requires a *facility to determine the usefulness of a new solution for future problem-solving*.

7.6.2 Process Model

On the basis of the above discussion, a process model for concrete road bridge design has been developed that integrates the two approaches, viz., heuristic and *case-based approaches* [52]. It consists of a *Rule-based-inference-Synthesis-Criticism* (RSC) model for the heuristic approach and a Case-Based-Design (CBD) model for the case-based approach. These two models are briefly described below.

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RSC Model

The RSC model consists of three process engines, viz., a *rule-based inference engine* (RBIE), a *synthesizing tool* and a *critiquing tool* as shown in Figure 7.26. RBIE uses the knowledge represented in the form of production rules for site data processing, layout planning, precondition generation for synthesis and preliminary dimensioning, decision making and overall process control. The synthesising tool uses the knowledge in the form of decomposition tree and elimination constraints for conceptual design of structural systems. The critiquing tool uses evaluation criteria represented in the form of aspects to be critiqued, ratings and their weights. RBIE also invokes the well-structured algorithmic procedures (represented using conventional procedural programming languages) for performing any computations that may be required during the bridge design process [53].

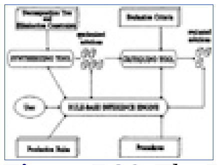

Figure 7.26 The RSC model

CBD Model

The CBD model consists of five processors, viz., RETRIEVER, ANTICIPATOR, TRANSFORMER, MODIFIER and STORER, as shown in Figure 6.5. The general framework and the generic tool, CASETOOL discussed in Chapter 6 are used for developing the CBD model.

7.6.3 KBES Development Tool

From the above sections it is clear that the following facilities are required for the development of an integrated KBS for concrete road bridge design:

- Rule-based inference with decision revision mechanism that works based on dependency-based backtracking.
- Decomposition tree and elimination constraint-based synthesis.

- Rating and relative importance-based critiquing.
- Case-based reasoning paradigm.

Besides these AI techniques, the KBES development requires the following.

- Data flow management between various tasks and modules.
- Static design data (e.g., standard sectional details, etc.) storage facilities.
- Procedural programming facilities.

On the basis of the above requirements DEKBASE (Development Environment for Knowledge-BAsed Systems in Engineering), explained in Chapter 3, was chosen for the development of the prototype system for bridge design.

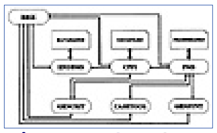
Figure 7.27 Organisation of DEKBASE

In addition to rule-based inference, design synthesis, design criticism and case based reasoning (explained in Chapters 4, 5 and 6) have been used in DEKBASE as given below and the organisation is shown in Figure 7.27.

- RBIE for rule-based inference.
- Frame base Management System (FMS) for solution data management
- Engineering Data Base Management System (ENDBMS) for static data management.
- Procedural Programming Interface (CPPI) for algorithmic computational procedures.
- GENSYNT for design synthesis.
- GENCRIT for design criticism.
- CASETOOL for building KBD model

7.6.4 SETHU: Architecture

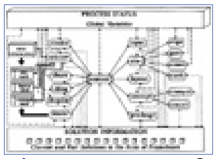
Figure 7.28 Architecture of SETHU

The architecture of SETHU is shown in Figure 7.28 and the various knowledge sources and the interaction between them are also indicated therein. The information flow from one knowledge source to another is maintained through global variables and frame bases. Global variables hold the information relating to the current status of the problem solving. This information aids all knowledge sources in making appropriate design decisions. The frame bases hold the solution information that is to be shared by various modules. The integration of two approaches, viz., heuristic and case-based approaches, is done in such a way that appropriate methodology is adopted depending on its suitability. That is, only when a case card is available and relevant cases are found for a given current situation, the case-based approach is resorted to.

7.7 Future Trends

The last decade saw developments in a number of related topics such as GAs, ANNs and concurrent engineering. The first two are tools or techniques that address specific problems. Concurrent engineering is a problem-solving model, in which multiple agents interact with each other to carry out tasks, using proper feedback and revision mechanisms. ANNs and GAs model ideas from nature for problem solving. GAs combine Darwinian theory of survival-of-the-fittest and natural genetics to form a robust search mechanism. As AI programs primarily use state-space search to arrive at solutions, use of GAs for search can improve AI-based problem solving. ANNs demonstrate an ability to learn from examples and rapid processing of information, which are not inherent characteristics of classical KBSs. KBSs and ANNs can be considered to be complementary and can be integrated to form a system that exploits the advantages of both the technologies. A brief description of the use of these tools with KBSs or other AI techniques are presented in the following sections. Also, the concept of the concurrent engineering model and its use for real-life engineering problem solving are presented at the end.

7.7.1 Genetic Algorithms

The adaptive nature of a genetic search simulates learning from the problem environment as the search progresses. Such learning guides the search technique to arrive at global optimal solutions. Integration of GAs and KBSs have been attempted by a few researchers in order to exploit the advantages of both systems.

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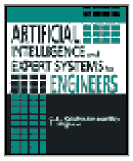

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Integration of GAs with Expert Systems

Powel et al. [54] introduced a technique called *interdigitation*, which effectively combines numerical optimisation techniques, expert systems and GAs. The technique worked successfully for engineering design optimisation problems. Powel used GA for global search and expert system and numerical optimisation for local hill climbing. The authors used an expert system as a preprocessor for GA-based design optimisation of structural systems. The ranges of design variables and values for other GA parameters are selected by an expert system, which has a knowledge base containing knowledge on the nature of the problem being solved and knowledge gained based on many such problems solved in the past. As the progress of optimisation and convergence to a globally optimal solution very much depends on the ranges of variables selected and the values selected for GA parameters such as probabilities of crossover and mutation, population size and convergence criteria adopted, it is required to get the most appropriate values so as to improve the efficiency and effectiveness of the problem-solving technique. Such serial integration of KBS and GA proved to be very useful in large problems of engineering design.

Hamada et al. [55] presented a hybrid model for GAs and KBSs for production planning in steel plants. They have decomposed the problems into subproblems, and then combined procedural methods, a rule-based expert system and a GA. First, procedural programs are used for charge grouping, then an expert system is used to generate coarse solutions and finally the charge group ordering is optimised using GAs. This is also a serial approach of integrating KBS and GA.

Another manner in which the concepts of KBS and GA are integrated is by augmenting the operator crossover and mutation using domain knowledge. Grefenstette et al. [56] developed a greedy, heuristic crossover operator for the classical travelling salesman problem. Augmentation of the operators with domain knowledge helped in reducing the search space, resulting in faster convergence.

Classifier Systems

As GAs are primarily adaptive search techniques, the implicit learning that takes place during the problem solving can be exploited for improving search in a KBS. Classifier systems, such as Genetics-Based Machine Learning (GBML) systems, use genetic search as their primary discovery of heuristics [57]. A classifier system consists of three components, viz., rule and message system, apportionment of credit system and GA. The rule and message system is a kind of production rule used in KBSs. In classifier systems, rules are represented as fixed-length strings. The rule and message system forms the computational backbone of the system. Information flows from the environment through the detectors (eyes and ears of the classifier system), where it is decoded to one or more fixed-length messages (strings). These messages are posted to a message list, where they can activate string rules called classifiers. On activation, a classifier posts a message to the message list. These messages can then invoke other classifiers (just as addition of new working memory elements that fire further rules) or cause actions to be taken through the action triggers of the system called effectors. This simulates combining environmental clues and internal thoughts to determine what to do and think next. Classifier systems activate rules parallelly in contrast to the sequential activation of rules in classical expert systems. Also, rating of rules, which are programmer specified in expert systems, are generated in classifier systems. The GA works on the binary coded messages in the message list (rules) to generate new rules using the operators, reproduction, crossover and mutation. Such generation of new rules, called *rule discovery*, plays an important role in genetic-based machine learning. Such integration of KBS concepts and GA concepts can find many applications in ineering problem solving.

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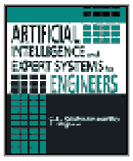

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GA methodologies in conceptual design

A totally different type of integration between GA concepts and AI-based design concepts has been presented by a research group at the University of Sydney. It is neither a serial nor a parallel integration, but the GA concepts such as natural selection (reproduction), crossover and mutation are used in AI-based techniques such as analogical reasoning. Hibs and Gero [58] have presented an evolutionary process model for engineering design. They have described a model of design as a series of transformation processes and extend that model initially to include the behaviour of the designed artifact in its environment. This extended model is then recast through an analogy with natural evolution as an evolutionary process model of design through the inclusion of the evolutionary style processes of cross over and mutation and the introduction of design genes and the notion of inheritance from one generation to the next. The concept of design crossover proposed by Hibs and Gero has a mechanism to combine different design concepts to achieve an entirely new behaviour. It is regarded as a combination of individual design genes or their parts, that is, a blend of sets of instruction for production related to two or more structures. Jo and Gero [59] proposed design mutation as a computational approach to creative design. Design mutation, operating on design prototypes as the representation schema, plays the role of a transformation process which produces new design prototypes through the cumulative generation and selection of mutated variables. Gero and Maher [60] proposed a computational model of creative process in design, which is founded on the use of mutation and an analogy process working in tandem using design prototypes as the representation schema. An analogical reasoning model is adopted for finding an analogous situation and using the knowledge from the previous situation to the new situation. Two useful techniques are derived from research in AI, viz., memory indexing and transformation, that help to carry out analogical reasoning in the creative design process. Memory indexing is used to facilitate information flow across contexts on which analogical reasoning is based. Design prototypes are grouped and retrieved according to their similarities of characteristics through indices. The indices are related to specific knowledge categories, viz., functions, structures and behaviours. Once an appropriate source design prototype is identified, it is required to transform the knowledge required to establish its relevance to the new design context. In the model for creative design proposed by Gero and Maher [60] the current context is defined by the selected design prototype in the target space. The source knowledge for accommodating the introduction of a new variable in the target space is the retrieved design prototype. They have used a structure-mapping approach to implement the same.

Integration of the concepts of GAs and AI techniques at different levels of abstraction can lead to many useful models for engineering problem solving. Increased activity of research and development in evolutionary computing and genetic algorithms indicates that a number of promising tools and techniques are on the anvil, for the engineering community.

7.7.2 Artificial Neural Networks

ANNs develop their own solutions from examples for a class of problems. They are also called *connectionist systems*, that simulate the low-level operations of the central nervous system. The desirable information-processing characteristics are manifested in the brain such as learning, generalisation and error tolerance, and they are captured and mimicked in ANNs. An ANN can be visualised as a collection of neurons interconnected to form a network. The neurons in the network process information parallelly and collectively within the structure of the network. Neural networks can be classified into different types based on the connection patterns of the neurons, mode of operations and the way the networks are trained. Appropriate combinations of these characteristics are to be formed depending on the problem being solved. A typical ANN is shown in Figure 7.29 that has a feed-forward connection scheme and synchronous operations of all neurons (nodes or cells). For the network shown in the figure, a Generalised Delta Rule (GDR) is adopted for training. Networks that use GDR for training are called *back propagation networks*, since training process requires errors measured at output neurons to be propagated backward through the different layers of the network. The network shown in the figure has three layers of neurons, viz., an input layer, an output layer and a hidden layer. Information about the features of the problems are presented to the network at the input layer. The solution is obtained at the output layer. Problem-solving activity is performed at the hidden layer (there can be any number of hidden layers) [61]. Lapdes and Farber [62] have suggested additional layers for more efficient solution of problems. As the working of ANNs is available elsewhere in the literature, it is not attempted here. Only the issues related to integration of ANNs and KBSs are described.

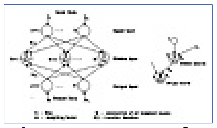

Figure 7.29 Schematic representation of a layered feed-forward ANN

The basic difference between ANNs and KBSs is that ANNs do not require a knowledge base or equivalent during problem solving. But they require a number of solved problems (input and output sets) in order to train the network. KBSs and ANNs can be combined together so as to take advantages of their strengths. Johnston et al. [63] implemented a rule-based system within a neural network environment for scheduling the activities of a space telescope. A feed-forward back propagation has been integrated with a set of production rules to develop a Gearbox Design Supervisor. Several approaches of integration of ANNs and KBSs were presented by various researchers [64–70]. Some typical approaches as reported by the above authors are briefly presented here, in order to give an overview on the topic to the reader.

In most approaches KBSs are used as the basis for developing ANNs or vice versa. Such an approach is useful, where one model is available and it is expected that the other model will provide better problem-solving characteristics. Such an integration is called developmental integration.

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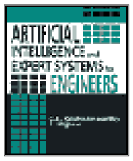

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In cases where neither of the models exist and it is easier to develop one model first and then use it to generate the other, a transposition integration can be adopted. Fu [71] presented a transposition scheme, in which a KBS is mapped into an ANN scheme. Such an approach is useful, when an improvement is sought to get more generalised solutions. In Fu's model, a rule is transformed into a link in the ANN and a conclusion in the rule base is mapped onto a neuron, strength of a rule is translated to a weight and the inference process is characterised by propagating and combining activation. In this model, a rule will fire, if a premise node is activated. A conclusion is drawn from the level of activation of an output neuron. The system can be made to adapt to a changing problem environment by implementing a back propagation learning scheme which will work in a recursive manner.

A trained ANN can also be transformed into a KBS, in which each neuron is converted into a rule [69]. The antecedents of the rule are formed using the weights of the input connections to a layer of hidden neurons and the biases associated with the hidden neurons. Similarly significance of the rule is formed by weights of the connection to the output neurons. This form of integration can be adopted in cases where one has to generate knowledge after solving a large number of example problems due to lack of available knowledge. This approach can also be adopted in cases where a KBS is preferred in order to have better transparency of the process.

A third type of integration is termed exemplification, in which an ANN is queried to generate a set of rules to develop a KBS or a KBS is used to generate examples for training an ANN. In transposition methods, there is a one-to-one correspondence between the components of a KBS and an ANN. In cases where such a correspondence cannot be established, the exemplification approach is desirable. But it may be noted that an ANN can provide generalised solutions, which are not available in the knowledge base of a KBS. In the second model of exemplification, heuristic knowledge is extracted by carrying out a sensitivity analysis of an ANN. This heuristic knowledge is used to extend the knowledge base of a KBS. Since an ANN adapts itself to changing problem environments, this approach helps in refining the knowledge base. One has to be very cautious in this kind of integration, because the quality of derived knowledge very much depends on the quality of examples selected for training the ANN. Bochereau et al. [70] and Fu [71] have presented cases employing this type of integration. Extraction of decision rules in a legal domain from a multilayer neural network is presented by Bochereau. A universal system for translating the mapping functions of a back propagation ANN into a set of production rules is presented by Fu [71].

The schemes for integrating ANNs and KBSs discussed so far finally produces either a KBS or an ANN at the end. The objective of the approach is to generate one model from the other. But a more useful approach is to evolve a model, in which both an ANN and a KBS work together to solve a problem. The advantages of both the models can be exploited here for the solution process. Two basic approaches of such usage of ANNs and KBSs were tried and a comprehensive review is presented by Kartam et al. [69]. There are serial and parallel operations. In the serial operation, one component (ANN or KBS) processes the information before the results are passed on to the other. Whereas, in parallel operation, both ANNs and KBSs work in parallel on parts of the problems, to which they are best suited. A brief review of work already reported in the literature [69] is presented below.

Barker [64] proposed a hybrid approach for the analysis of the financial welfare of a business, in which an expert system shell controls the overall functions and the neural network development environment is trained using case histories stored in a database. In the work of Dagli [67], a KBS is used to describe the problem domain for generating optimal Flexible Manufacturing System (FMS) schedules. Then two ANNs are used, a back propagation network for classifying jobs and a Hopfield network for generating optimal sequences of jobs. The Hopfield neural network is primarily an optimising ANN, which takes the time to complete different jobs as input and generates a plan of sequence that minimises the time to complete an entire set of jobs. This model can very well be used in many applications in which problem description and general control parameters are handled by a KBS, whereas recognition of multiple patterns represented by case histories are the ANN’s task.

Use of a KBS for interpretation and analysis of output of an ANN is very useful in cases where an in-depth reasoning and justification for the result obtained from an ANN is required. This approach of integrated usage of a KBS and an ANN is very useful in classification and diagnosis type of problems. Full exploitation of capabilities of an ANN and a KBS is achieved by this approach. Ferrada et al. [65] developed an activated sludge troubleshooting guide and a rotary system fault diagnosis guide. Ace [73] has reported a work based on a similar model, in which the system detects and diagnoses chatter in cold strip mills.

The models presented above fall under the category of serial operations of ANNs and KBSs. A typical system using the model of parallel operation is developed by Rabelo and Alptekin [66] for generation of optimal manufacturing schedules for FMS. In this, a KBS uses an ANN to obtain implicit features of a database, develop innovative knowledge acquisition strategies and provide an initial approach to problem solving.

There are a number of problems where neither ANN nor KBS can give satisfactory solutions and in such situations a hybrid approach is highly recommended. But one has to closely examine the problem and identify the processes that are suitable for respective models and then adopt an appropriate hybrid scheme for implementation.

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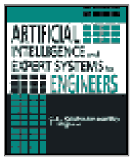

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7.7.3 Concurrent Engineering

The classical design approach considers only the behavioural aspects of the artifact during the design stage, in which the artifact is designed for strength and sometimes for serviceability requirements. Such a design may be acceptable from the primary strength considerations, but it may have deficiencies from manufacturability, assembly, recyclability, etc. An ideal design should cater to the life-cycle requirements of the product; the life-cycle consisting of both the user’s life-cycle requirements as well as the life-cycle cost of the product. Concurrent engineering is a practice of incorporating various life-cycle values into the early stages of design. It deals with organisation of information and processes for concurrent consideration of difficult life-cycle requirements.

The different processes involved in concurrent engineering design are communication between different agents involved in design, design reviews of different stages of development, application of value engineering, monitoring of quality at every stage, etc. Automation of the tasks enumerated above on computers leads to computer-aided concurrent engineering. Though the concept of Computer-Aided Concurrent Engineering Design (CACED) was talked about many years back, it could not be realised due to non-availability of appropriate tools and techniques for implementing the concept. Development of AI-based tools and evolution of models for multiagent problem solving in the past few years have made CACED a reality.

Many of the early tools were aimed at assisting human engineers during different stages of the design process. Later works concentrated on identification of generic methodologies that can be used in any application domain. The key issue to be addressed in CACED is a tool or technique for evaluation of a candidate design from the consideration of different life-cycle values. Design For Assembly (DFA) is a program by Boothroyd and Dewhurst [74], which reviews a candidate design from the assembly point of view. It is considered to be a pioneering work in simultaneous engineering. Though usage of the program was difficult, acceptability of DFA in the industry was high becuase of the sound methodology it had. Simmons and Dixon [75] explored use of AI technology for CACED. Tools such as feature-based design environment and object-oriented programming were used by Turner and Anderson [76]. A team at Carnegie Mellon University worked on a powerful design representation scheme to have consistent linkage between geometry modeling systems and assembly systems [77].

Ishii et al. proposed Design Compatibility Analysis (DCA) which is a model of design reviews in which experts from different domains judge the candidate design from different points of view [78,79]. Although this framework does not consider every aspect of life-cycle design it has proved to be versatile and adaptable. This method models *round-table* design reviews, wherein different experts discuss the proposed design and suggest improvements. The suggestions focus on modification of a candidate design but may also suggest respecification of the process (such as use of an alternate machine etc.) or negotiation for modifying user requirements. The model also checks how the design team combines everybody’s comments and makes compromises. It uses a knowledge-based technique for computing a normalised measure of compatibility. The model allows the designers to check the candidate design at any time in the development process by comparing the proposed design with the compatibility knowledge base. The model carries out a reasoning about characteristics of the candidate design and their implications on the specifications. A rule-based approach is adopted for such reasoning. A schematic presentation of the DCA is shown in Figure 7.30.

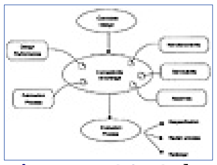
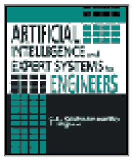


Figure 7.30 Schematic presentation of DCA

DCA proposed a quantitative index called a compatibility index, which is computed after analysing the individual elements/attributes relative to the specifications. The compatibility knowledge base is used to map adjective descriptors such as excellent, very good, good, fair, bad, etc. to numerical code between 0 and 1. A match index is computed after a design compatibility analysis, in which ratings assigned to different attributes of the artifact are also considered. DAISIE (Designers AId for SImultaneous Engineering) is an object-oriented programming environment, which is an implementation of the life-cycle design concept DCA [80]. Several life-cycle design aids have been developed using the framework DAISIE.

Appropriate integration of the concepts presented in Chapters 4 and 5 of this book, viz., design synthesis and design criticism (design evaluation), provide ideal mechanisms for developing a model for computer aided concurrent engineering. A typical example of simultaneous consideration of different life-cycle values in a design problem was presented earlier in the chapter for the design of car body shapes, wherein the designs generated by the synthesis process are evaluated for stability, response, maintenance/repair, entry and exit, drag, visibility, ventilation, etc. The concept can be extended for concurrent engineering design of the whole automobile. Another example presented in this chapter, viz., building design in section 7.4, addresses issues such as knowledge processing in multiagent problem solving, existence of multiple solutions, qualitative as well as quantitative evaluation, consistency and compatibility maintenance, horizontal integration of different disciplines affecting the design and vertical integration of many phases of the design process. The SCM model is essentially a framework for CACED, with systematic representation of knowledge and use of appropriate knowledge-processing techniques at generate (synthesis), test (criticise) and modify stages.

The current trend in concurrent engineering is to include market and customer focus also in its realm. Research is also in progress to synchronise time, cost and quality improvements with customer demand. The main reason for not achieving this is due to difficulty in communicating between development, sales and marketing due to divergent competencies, languages and objectives. Integration of these issues in concurrent engineering is also essential for realising the objectives laid out for CACED.



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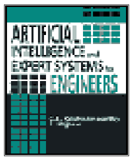

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Appendix I

This appendix describes the expert system development shell DEKBASE with the syntax and other facilities provided for developing expert systems in any domain. The rule base language of DEKBASE and facilities provided for creating and managing frames from rules are presented. The example rule bases presented in Chapter 3 are written using the syntax of DEKBASE. The information given in this appendix will help readers understand the examples and also use the shell given in the accompanying disk.

DEKBASE provides an elegant language for expressing the expert’s knowledge. The language is English-like and is highly readable. Such a syntax allows an expert (who is not familiar with computers and programming) to go through the knowledge base listing and understand the way the knowledge is expressed. The main form of knowledge representation is production rules and frames. It is possible to use multiple knowledge bases for building a prototype. Such a division of knowledge is usually dependent on the problem domain and on how knowledge pertaining to the domain can be further subclassified. Use of multiple knowledge bases promotes efficiency and encourages structured development of prototypes. The formal structure of a knowledge base in DEKBASE has the following form.

Title Statement
General Directives (*)
Variable Declarations
Variable Flags (*)
Variable Initialisations (*)
Statement of Goal/Goal Hierarchy
Rules
Information Definitions (*)
End Statement

Those items marked with an asterisk (*) are optional items. The rule bases are text files with an extension. RL extension (RL stands for Rule base Language). The rule base can be created using any text editor. A brief description of each item of the rule base language of DEKBASE is presented in this appendix. While reading the description the reader has to follow some notations:

- Information given in <...> is compulsory and should be replaced with an appropriate value by the user.
- Items of information separated by | are alternatives, of which only one should be used at the given position.
- Information in {...} is compulsory and one of the stated options must be provided.
- Information in [...] is optional.
- EOL is used to indicate end of a line.

Title Block

It contains the name of the knowledge base and some general information that is to be displayed at the beginning of a session with the expert system, when the rule base is loaded for inference. It has the following form:

```
TITLE <title-string> EOL
```

The title string identifies the rule base and it can have a maximum of 80 characters.

General Directives

This is an optional item. DEKBASE provides four directives as shown below:

```
CONFIDENCE      { ON | OFF }
THRESHOLD       <value>
GOALSELECT      { ON | OFF }
CHAINMODE       { FORWARD | BACKWARD | HYBRID }
```

The CONFIDENCE directive controls the mode of confidence evaluation. This directive has significant influence on the inference process, since the interpretation of rules and facts with and without confidence factors is different. Even though confidence factors are specified in rule base, a directive, CONFIDENCE OFF, ignores them.

The THRESHOLD directive is used to specify a threshold confidence. A condition is deemed to have been satisfied only if the overall confidence of the premise exceeds the specified threshold value. This can take a value between 1 and 99. The threshold directive is ignored, if CONFIDENCE is set to OFF.

In a problem domain, a hierarchy of goals can be specified. It is required when the knowledge engineer wants to give an option of selecting a part of a knowledge base for inference. If the GOALSELECT directive is set to ON in the rule base, the inference process prompts the user for selecting the required goals from the hierarchy by displaying the relevant goals. The default of this directive is OFF and in that case all the goals specified in the rule are pursued.

The CHAINMODE directive is provided to specify one of the three available inference modes, viz., backward, forward and hybrid chaining for inferring the rule base. Though the knowledge engineer sets the directive in the rule base, the user can modify it during run time. By default, CHAINMODE is set to backward chaining, the most frequently used inference mechanism.

Variable Declarations

Facts are represented as variables having values assigned to them. DEKBASE expects all the variables used in the rule base to be declared. DEKBASE allows variable names of up to 80 characters, which can even have blank spaces in them. For instance, ‘design of lateral load resisting system completed’ is a valid variable name in DEKBASE. The variables are declared by prefixing the name of the data type with the variable name. The data types supported by DEKBASE are:

BOOLEAN: A boolean variable can take a value True or False.

INTEGER: This data type is identical to *int* of C programming language and can lie in the range -32768 to 32767.

DOUBLE: This data type represents a *floating point* value, and can lie in the range 1.7E-308 to 1.7E+308.

Integer and double data can be used in expressions with different arithmetic operators supported by DEKBASE. They are:

+ adds the operands

- subtracts the operand in rhs from that in lhs of the sign (This can also be used in unary mode)

* multiplies the operands

/ divides the operand on lhs by that on right hand side

^ raises the operand on lhs to the power of that on left hand side

( ) is used to represent complex expressions for their clarity and also for overriding the precedence of the operators

In addition to the above, DEKBASE also provides some functions, viz., SIN, COS, TAN, ABS and CONF, which can be directly used in expressions. The first four functions are mathematical functions, whereas the function CONF returns the confidence factor attached to a fact passed as argument to it. The numeric quantities can be compared using the logical operators, <, <=, >, >=, == and !=. The meaning of the operators is the same as those in C.

STRING: This data type can be used to represent strings. String constants with up to 80 characters can be assigned to a string variable.

GROUP: This data type represents set. Any number of strings can be assigned to a variable of this type.

A declaration statement in DEKBASE has the following form:

[scope] <data-type> <list of variables separated by commas>

The scope of a variable can either be GLOBAL or LOCAL. By default, all variables are LOCAL, which means that these variables are created when the rule base is loaded and are removed when the inference engine loads another rule base. GLOBAL variables remain in memory until the inference engine exits, but they will be accessible to another rule base unless that rule base also declares the variable as GLOBAL.

There can be any number of declaration statements. Each statement must start on a new line. A single statement can be extended over several lines by appending a backslash character at the end of the continued lines.

Variable Flags

In addition to type, scope and value of variables, there are other characteristics called flags, which can control the inference process. Default values are used if flags are not specified for variables. Declaration of variable flags has the following form:

[Flag]<list-of-variables> EOL

The four flags supported by DEKBASE are HIDE, CLEAR, OVERRIDABLE and VOLUNTEERABLE.

Setting a HIDE flag to a variable makes it invisible to the explanation facility. Usually for variables which represent intermediate nodes in a knowledge net or which are of temporary nature the HIDE flag is set. To use a set of rules in a cyclic manner such that after reaching the goal, the inference process has to be restarted once over again by removing a few facts from the context, a restart action can be specified in a rule. If the CLEAR flag of a variable is set, the variable or the fact will be removed from the context when restarting occurs. Setting the OVERRIDABLE flag makes the inference process notify the user when a fact is established, so that the user gets an option to change the value of the variable. Setting the VOLUNTEERABLE flag makes the inference process query the user for a value for the variable and for the user to give a value instead of arriving at it after inference. If the user chooses not to supply a value, it can be done. Depending on the situation, the knowledge engineer sets appropriate flags for variables in a rule base. It may be noted that setting of flags itself is optional.

Variable Initialisations

The knowledge engineer can initialise variables by assigning values to them in an explicit manner. Especially since the forward chaining inference process is data driven, it needs all the facts to be established by input data to be available in the context before the inference process starts. This is achieved using this facility. Depending on the variable type, the initialisation statements vary. The different forms of variable initialisation statements are given below.

Boolean variables:

SET <list-of-variables> [CF value] EOL

This statement makes the value of all the variables specified in the list TRUE, with the specified confidence values. If the CF value is not specified, it is assumed to be 100. The following statement can be used to set a boolean variable to FALSE.

SET NOT <list-of-variables> [CF value] EOL

Numeric variables: Integer and double type of variables can be initialised using the statement:

SET <variable-name> = [+] <value> [CF value] EOL

String variables: The initialisation statement for string variables has the form:

SET <variable> IS <string-constant> [CF value] EOL

Group variables: Since a group variable can hold any number of values, it can be initialised in the following form.

```
SET <variable> CONTAINS <value1 [CF value]>
                         <,value2 [CF value]> ...
```

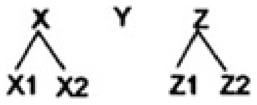
Goal Statement

This statement is mandatory in a rule base and there can be only one GOAL statement. The same goal statement is used to specify a single goal or a hierarchy of goals. A single goal can be specified as:

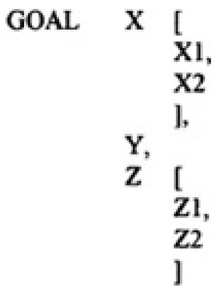
GOAL <goal-variable>

If it is required to specify a hierarchy of goals, it can be done as shown below.

Consider a goal tree as shown. Let there be seven variables to be expressed as goals that are organised in the hierarchy as shown below.



This hierarchy can be specified using the following statement.



```
GOAL   X  [
            X1,
            X2
            ],
          Y,
          Z  [
            Z1,
            Z2
            ]
```

Rules

Rules form the basis of knowledge representation in DEKBASE. A rule is expressed in DEKBASE in the following form:

```
RULE  Rulename      EOL
IF          <antecedent1> EOL
<AND/OR>    <antecedent2> EOL
                        ...
THEN  <consequent1>  EOL
AND   <consequent2>  EOL
ELSE  <consequent-x> EOL
AND   <consequent-y> EOL
```

A rule name identifies a rule. It is also used for explanation to the query ‘how?’. When the user queries the expert system for ‘how a value is obtained for a variable?’, the system responds with the rule name, indicating that the rule with the name displayed is used for arriving at the value for the variable. A rule can have any number of antecedents or conditions and consequents or actions. Conditions can be combined through the operators AND and OR. The OR operator has higher precedence. An antecedent ultimately resolves to a boolean value irrespective of its various forms; i.e., all the conditions together evaluate to TRUE or FALSE. The antecedents can have different forms as described below.

a) Check whether a fact is established or not

<variable-name> IS_DEFINED [TH value]

This statement checks whether a fact involving the given variable is established or not. TH is the threshold; value specified, which is optional.

b) Check whether a boolean value is established or not

<variable-name> [TH value]

If the confidence value is on, then the fact is checked with the given threshold; otherwise confidence processing is ignored.

c) Compare strings

<variable-name> IS <value/variable-name> [TH value]

Here the right-hand side can either be a value (string constant) or another string variable for a which a value has already been assigned.

d) Check whether a set contains a value

<variable-name> CONTAINS <value1> [<value2> . [TH value]

The condition evaluates to TRUE if the specified values are available in the set defined by the variable on LHS.

e) Comparison of two expressions

The expressions on either side of an operator can contain numeric variables, arithmetic operators and the mathematical functions supported by DEKBASE.

The basic form of a consequent is the one that assigns a value to a variable for establishing a fact. Since deduction of a new fact involves assigning a value to a variable, this is the essential form of a consequent of a production rule. The various forms that a consequent can take are

a) Set a boolean variable to TRUE or FALSE

<variable-name> [CF value] EOL	sets TRUE
NOT <variable-name> [CF value] EOL	sets FALSE

b) Assign a value to a string variable

<variable-name> IS <string-var | string-constant> [CF] EOL

c) Include a value in a set

<variable-name> CONTAINS <list of values> [CF] EOL

d) Assign a numeric value of an expression to a variable

<variable-name> = <expression> [CF value] EOL

e) Assign a numeric value returned by a C function to a variable

<variable-name> = <C-function> EOL

Here the C function should return a value of type Integer or Double.

f) Carry out unconditional actions

Many times it may be necessary to carry out unconditional actions in both the antecedent and consequent parts of a rule. Traditionally actions are not meant to be used in the left-hand side of a rule. Such a facility has advantages and disadvantages. Use of actions in the IF part of a rule should be done with sufficient reason and caution. Certain actions, when used in antecedents, cause problems especially when uncertain reasoning is being carried out. Various unconditional actions that should be available in a rule are the following:

a) Facility to load another rule base

This action causes the inference engine to suspend the inference process of the current knowledge base and load a new knowledge base for inference. The following rule loads another rule base.

```
IF          design for vertical load resisting system completed
THEN        LOAD lateral
```

The knowledge base should contain a rule base with the name ‘lateral’ and should be linked together with other rule bases. Only then it can be loaded.

b) Run an external program

This action temporarily suspends the inference process and executes an external program (an EXE program in DOS), which is available in the current directory. This feature can be used to carry out some analysis using data generated as a result of the inference process. It can also be used to load other interactive programs to obtain additional data.

```
IF          bridge type is selected
THEN        RUN dispfig.exe
```

When the above rule is fired, the executable program DISPFIG.EXE available in the current directory is executed.

c) Write items to a data file

The WRITE action facilitates the file write operation. This is required to write values from the context to data files, so that either external programs invoked later can access them or the data can be used for any further processing. This facility is essential to build large prototype expert systems, in which external programs interact with the expert system. The syntax for write is as shown below:

```
WRITE      <filename> > [NUMERIC: <expression list>]
                        [STRING: <variable | value list> ]
```

The following statements are two typical WRITE statements.

```
WRITE      outdat NUMERIC: 2, 3.0, il*i3+230
WRITE      outdat NUMERIC: 2, 3.0 STRING: shape, size
```

If the file is not there in the working directory, then the file is created before writing. If the file already exists, then the data are appended to the existing file.

d) Read items from a file

Just as the file output facility, the file read facility helps in organising data and also improves interaction with external programs. By using this facility, the inference engine can read the output generated by external programs. As the values read from the file are assigned to rule base variables, reading of values establishes new facts in the context. The syntax is:

```
READ <filename> <variable list>
```

e) Display a text message

This is a very useful facility, using which a text message can be displayed during the inference process. It helps the user of the expert system monitor the progress of the inference process. Display of appropriate messages with values taken from the context allows the user not only to know the state of inference but also helps in having a better interaction with the expert system. The statement has the following form:

```
DISPLAY <display-tag>
```

The display tag can be an identifier made up of any combination of alphanumeric characters. This is explained later in *information definitions*

f) Show a picture

The display of messages with pictures can convey information in a much more effective manner than display of text messages. The facility should display figures created using standard graphics packages or scanned images. The statement has the following form:

```
SHOW <name-of-bit-map-file>
```

The bitmap file should be a valid bitmap file with an extension .BMP.

g) Undefine a variable

Just before start of the inference, the context is empty and all the rule base variables are set to be UNDEFINED. This state of a variable changes the moment a value is assigned to it. If the inference has to set a variable back to UNDEFINED, this facility can be used. The syntax for this is

```
UNDEFINE <variable-name>
```

h) Restart the inference process

This action directs the inference engine to suspend the inference process and start again from the beginning. The context is reset with making all the variables UNDEFINED. A facility of selective removal of items from context would be very useful, when the action restart is invoked.

Information Definitions

Information definitions are some facilities provided by DEKBASE to handle text messages. Text messages can be used in any of the following three situations.

1. DISPLAY messages from within the rules
2. EXPLAIN to the user some variables if required
3. QUERY the user with a meaningful question for data input

The syntax of the display message is:

DISPLAY <display-tag> "text message" [<list of variables>]

When a rule having a DISPLAY action in the consequent is fired, the inference engine displays the text message given in quotes to the output screen. The text message can be of any size. But a maximum size of 20 lines is appropriate, since it will not scroll up. Values of variables can also be displayed within the text message using a format specifier. The following example illustrates this.

```
IF          length > = 2 * breadth
THEN        lateral load analysis is required
AND         DISPLAY lla
```

Here, lla is a tag associated with a text message. The expansion for the tag is provided below:

```
DISPLAY lla "
It is not required to analyse the building for
lateral load as the length and breadth are %% and %%
respectively.", [length, breadth]
```

When the text message given within the quotes is displayed, the first %% symbol is replaced by the current value of the variable *length* and the second %% symbol is replaced by value of the variable *breadth*.

The EXPLAIN facility is used to associate an explanatory text with a variable. During the inference process, if the user wants further explanation of a variable, then a text giving the required explanation can be associated with the variable. The syntax has the following form:

EXPLAIN <variable-name> " text message"

During the inference process, if it is required to obtain the value of a variable from the user, the inference engine displays the variable name on the screen followed by a question mark as a prompt. In case only short variable names are used, the user may not know what is expected. Associating a QUERY with a variable helps in such situations. The meaningful query associated with the variable is displayed when data for the variable are required from the user. The query has the following syntax:

QUERY <variable-name> " query ", [<low>, <high>]

Whenever a query is associated with a variable, it is also possible to define a lower and upper bound value for the variable. Range specification is optional. During the inference process, if the user input does not satisfy the specified range, the inference engine does not accept the value. It keeps prompting the user until a value within the range is obtained.

Other Features

DEKBASE provides many other features, which help in better organisation and development of rule bases.

Comments in rule base

As in any programs written in high-level languages, comments are useful for documenting the knowledge bases. Comments can be specified in two ways in DEKBASE rule base. In the first form, all the text to the right of a # symbol ignored. The second form is similar to that in C language, i.e., any text with a /* and */ symbol is ignored by the compiler.

File Inclusions

DEKBASE allows one level of file inclusions. Any number of files can be included in a rule base. The syntax for file inclusion is:

    $INCLUDE <file-name>

The $ symbol should start in the first column itself and the file name should be given in single quotes. This facility can very well be used for better organisation of rule bases. For example, all the variable declarations can be put in one file, and so all the infodefs. The rule base will have only the rules with two include statements for including variables declarations and directives, and for including infodefs.

Frames

Use of frames for knowledge representation is a major facility of DEKBASE. It helps in better organisation of declarative knowledge. Implementation of frames in DEKBASE is briefly described in this section.

A frame is a collection of slots (attributes) and values attached to the slots. Frames are created and used during the inference process. A collection of frames is called a frame base. Any number of frame bases can be created in a knowledge base. But only one frame base can be active at a time. It is also possible to dump a frame base to a disk file and load it again during inference. Frames are global in nature and all the rule bases can access them. Rules can interact with the frames either for storing or accessing information. Frame operations can be specified either in the antecedent or the consequent part of a rule. Various operations permitted on a frame base are discussed below. The statements described below for frame operations can be used directly in rules.

The facilities for frame operations are divided into two groups, viz., those for managing frame bases and those for managing frames.

Frame Base Operations

A frame base is a collection of frames. It is not necessary that the frames in a frame base be related. Any number of frame bases can be created during run time, but only one can be active at a time. Operations on frame bases and frames are considered unconditional actions by the inference engine and are carried out as and when encountered. A brief description of the syntax for six frame base operations is enumerated below.

1. Creating frame bases

    FCREATE_FBASE <list-of-frame-bases>

All the frame bases in the list are created using the above statement.

2. Selecting a frame base

Before commencing any frame operation, the frame base has to be selected to make it active. The following statement selects a frame base.

    FSELECT_FBASE <frame-base>

3. Deleting frame bases

When a frame base is deleted, all the frames in the base are also deleted. The following statement deletes frame bases.

    FDELETE_FBASE {list-of-frame-bases>

4. Saving frame bases

A frame base can be stored as a disk file. The name of the file is the same as that of the frame base. Hence, it is recommended that the name of a frame base be limited to eight characters. DEKBASE adds an extension .FBS to the file name for identification.

    FSAVE_FBASE <list-of-frame-bases>

5. Loading frame bases

The following statement is used to load frame bases during inference.

    FLOAD_FBASE <list-of-frame-bases>

Frame Operations

A frame is always referred to by its unique name. In DEKBASE, frames can have any number of slots and each slot can have any number of values attached to it. The value attached to a slot should be of any of the data types, integer, double or string. Instances of a generic frame can be created using the frame duplication facility provided. The various frame operations are enumerated below.

1. Create frames: All the frames given in the list are created.

FCREATE_FRAME <list-of-frames>

2. Delete frames: All the frames in the list are deleted.

FDEL_FRAME <list-of-frames>

3. Add attributes to frames:

```
FADD_ATTR<frame>,
          {FINTEGER|FDOUBLE|FSTRING},<attr_list>
```

4. Delete attributes from frame:

FDEL_ATTR <frame>, <list-of-attributes>

5. Add values to attributes: This action inserts a value to the position specified. The value can also be a general expression in terms of rule base variables. In the interactive mode, the user has to ensure that the value supplied is of the same data type specified as that of the attribute. The syntax has the following form:

FINSERT_VAL <frame>, <attribute>, <position>, <value>

6. Delete a value: This action matches the value specified against the existing values in the slot and deletes the value. If a value at the intermediate position is deleted, the position of all the subsequent values gets modified.

FDEL_VAL <frame>, <attribute>, <value>

7. Modify a value: This action modifies the value existing at the specified position by the value supplied.

FMOD_POS <frame>, <attribute>, <position>, <value>

8. Delete value at specified position: The value of an attribute at the specified position is deleted.

FDEL_POS <frame>, <attribute>, <position>

9. Duplicate a frame: This action duplicates the specified frame. Each duplicated frame is an instance and is identified by an instance number. For example, the ith instance of a frame ‘beam’ is given a name ‘beam[i]’. The instance number varies from the stated starting and ending values.

FDUPLICATE <frame>, <start>, <end>

The two knowledge bases presented in Chapter 3 are written using the syntax of DEKBASE. The source code of one of the examples is provided in the accompanying floppy diskette.

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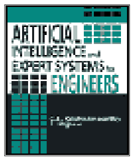

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Appendix II

This appendix lists decomposition and preconditions files for Examples 2 and 3 on design synthesis presented in Chapter 4. The representation follows the syntax of GENSYNT, which has been described in the chapter. For each of the examples, the snapshot of the output, which in this case is a typical solution, is also enumerated.

Example 2

```
TITLE Decomposition for building outline generation
SYSTEM
    site, building, service, floor, core, s_area
PROGRAM
  BuildDim, CoreDim, NumCores, CorePos,NoFloors,SerArea
DECOMPOSITION

SYSTEM Site

length          EXPRESSION       length
width           EXPRESSION       width
req_area        EXPRESSION       req_area
building        SUBSYSTEM        building

END_SYSTEM

SYSTEM building

peak_pop        EXPRESSION       peak_pop
max_length      EXPRESSION       site.length-10
max_width       EXPRESSION       site.width-10
perc_length     ONE_OF           P100,P90,P80
```

```
perc_width      ONE_OF            P100,P90,P80
length          PROGRAM  BuildDim(building.max_length,
                                  building.perc_length)
width           PROGRAM  BuildDim(building.max_width,
                                  building.perc_width)
service         SUBSYSTEM         service
floor           SUBSYSTEM         floor
END_SYSTEM

SYSTEM service

pos_core  ONE_OF     center,sides
num_cores PROGRAM    NumCores(service.pos_core)
core      SUBSYSTEM       core
s_area    SUBSYSTEM       s_area
IF(service.num_cores > 1)
THEN FOR c_count=1,service.num_cores REPEAT core

END_SYSTEM

SYSTEM core

length    PROGRAM         CoreDim(len,service.pos_core,
                                building.peak_pop)
width     PROGRAM         CoreDim(wid,service.pos_core,
                                building.peak_pop)
area      EXPRESSION            core_length*core.width
left_x    PROGRAM               CorePos(x,c_count,
               service.pos_core,core.length,building.length)
bot_y     PROGRAM         CorePos(y,c_count,
               service.pos_core,core.width,building.width)

END_SYSTEM

SYSTEM floor

num_floors     PROGRAM          NoFloors(site.req_area,
               building.length,building.width,s_area.area)

END_SYSTEM

SYSTEM s_area

area      PROGRAM         SerArea(service.pos_core)

END_SYSTEM

CONSTRAINTS

IF(floor.num_floors >0)
THEN floor.num_floors <= max_floors
IF(building.length > 0)
THEN building.length/building.width <= 4
IF(building.width > 0)
THEN floor.num_floors*ht/building.width <= 10

END

PRECONDITIONS

length = 70
```

```
width = 50
req_area = 25000
max_floors = 15
peak_pop = 250
ht = 3.5
```

<u>Output Results</u>

Solution

```
site.length = 70
site.width = 50
site.req_area = 25,000
building.peak_pop = 250
building.max_length = 60
building.max_width = 40
building.length = 54
building.width = 32
building.p_length = 90%
building.p-width = 80%
floor.num_floors = 10
service.pos_core = sides
service.num_cores = 2
s_area.area = 400
core[1].length = 20
core[1].width = 10
core[1].area = 200
core[1].left_x = 0
core[1].bot_y = 11
core[2].length = 20
core[2].width = 10
core[2].area = 200
core[2].left_x = 34
core[2].bot_y = 11
```

Example 3

```
TITLE Decomposition file for preliminary design of gear trains
SYSTEM
gearbox,gear
PROGRAM
norows,shaftdia,ratio, velocity,module,checking
DECOMPOSITION

SYSTEM gearbox

max_length       EXPRESSION         length
max_breadth      EXPRESSION         breadth
max_height       EXPRESSION         height
power_in         EXPRESSION         power
in_speed         EXPRESSION         inspeed
out_speed        EXPRESSION         outspeed
in_shaft_type    ONE_OF             hollow,solid
no_rows          PROGRAM            norows(inspeed,
                                           outspeed)
no_teeth         EXPRESSION         input_teeth
in_torque        EXPRESSION  (power/gearbox.in_speed)
in_shaftdia_in   PROGRAM     shaftdia(gearbox.in_torque,
                             gearbox.in_shaft_type,2)
in_shaftdia_out  PROGRAM     shaftdia(gearbox.in_torque,
                             gearbox.in_shaft_type,1)
```

```
gear              SUBSYSTEM         gear
IF(gearbox.no_rows>1)
THEN FOR t_count=1,gearbox.no_rows REPEAT gear

END_SYSTEM

SYSTEM gear

shaft_type        ONE_OF      hollow,solid
gear_ratio        PROGRAM     ratio(t_count)
teeth_in          EXPRESSION  (18*gear.gear_ratio)
gear_velocity     PROGRAM     velocity(t_count)
gear_torque       EXPRESSION  (gearbox.power_in/
                              gear.gear_velocity)
shaft_dia_in      PROGRAM     shaftdia(gear.gear_torque,
                                      gear.shaft_type,2)
shaft_dia_out     PROGRAM     shaftdia(gear.gear_torque,
                                      gear.shaft_type,1)
gear_modules      PROGRAM     module(height,gear.teeth_in,
                                    gear.shaft_dia)
gear_type         ONE_OF      spur,helical
bearing_type      ONE_OF      tapered,radial
modules           ONE_OF      M1,M5,M10
check             PROGRAM     checking(gear.modules,
                              gear.gear_modules)

END_SYSTEM

CONSTRAINTS

IF(gear.modules == M1 )
THEN gear.check == 0
IF (gear.modules == M5 )
THEN gear.check == 0
IF (gear.modules == M10 )
THEN gear.check == 0
IF(gear.gear_velocity>400)
THEN gear.gear_type==helical
IF(gear.gear_velocity==400)
THEN gear.gear_type==helical
IF(gear.gear_velocity<400)
THEN gear.gear_type==spur
IF(gear.gear_type==helical)
THEN gear.shaft_type==solid
IF(gear.gear_type==helical)
THEN gear.bearing_type==tapered
END

PRECONDITIONS

length = 0.5
breadth = 0.5
height = 0.5
inspeed = 400.0
outspeed = 50.0
power = 40000.0
input_teeth = 18
```

Output Results

Solution

```
gear_box.num_rows = 2
input_shaft.type = solid
input_shaft.diameter = 0.3
gear_row[1].module = M1
gear_row[1].gear_ratio = 0.9
gear_row[1].type = helical
gear_row[1].shaft_type = solid
gear_row[1].shaft_dia = 0.3
gear_row[1].bearings = tapered
gear_row[2].module = M1
gear_row[2].gear_ratio = 0.8
gear_row[2].type = helical
gear_row[2].shaft_type = solid
gear_row[2].shaft_dia = 0.4
gear_row[2].bearings = tapered
```

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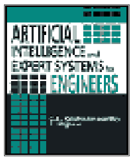

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Appendix III

This appendix lists the critiquing knowledge base and associated C functions for Example 2 described in Chapter 5. The knowledge representation follows the syntax of GENCRIT, which has been described in the chapter.

Example 2

The critiquing knowledge:

TITLE A constructibility critic for single-story concrete buildings

```
SYSTEM
  bldg_system,
  lng_layout¹
  trn_layout²
PROCEDURE
  DetermineNoOfSpacings,
  DetermineBmtoBmCompatibilityNumber,
  DetermineBmtoCmLngCompatibilityNumber,
  DetermineBmtoCmTrnCompatibilityNumber,
  DetermineInterferenceInSameDirection,
  DetermineInterferenceInAcrossDirection
CRITIQUE
SYSTEM lng_layout
{
  /* Item No. 1 */
  uniformity_of_longitudinal_spacing: WF = 1.0
  [rating=DetermineNoOfSpacings()]
  IF(rating == 0)
  {
          RF = 0
```

```
            REMARK: "The longitudinal layout is non-uniform, \
            with each bay spacing being different from the other"
  }
IF(rating == 100)
```

[1] system representing longitudinal layout

[2] system representing transverse layout

```
  {
            F = 100
            REMARK: "The longitudinal layout is uniform"
  }
  IF(rating >0 AND rating <=20)
  {
            RF=10
            REMARK: "There is a very high degree of \
            non-uniformity  in the longitudinal layout"
  }
  IF(rating >20 AND rating <=40)
  {
            RF=30
            REMARK: "There is a high degree of \
            non-uniformity in the longitudinal layout"
  }
  IF(rating >40 AND rating <=60)
  {
            RF=50
            REMARK: "There is moderate degree of uniformity \
            in the longitudinal layout"
  }
  IF(rating >60 AND rating <=80)
  {
            RF=70
            REMARK: "There is a high degree of uniformity in \
            the longitudinal layout"
  }
  IF(rating >80 AND rating <100)
  {
            RF=90
            REMARK: "There is a very high degree of \
            uniformity in the longitudinal layout"
  }
}
SYSTEM trn_layout
{
  /* Item No. 2 */
  uniformity_transverse_spacing: WF = 1.0
  [rating=DetermineNoOfSpacings()]
  IF(rating == 0)
  {
            RF = 0
            REMARK: "The transverse layout is non-uniform, \
            with each bay spacing being different from the other"
  }
  IF(rating == 100)
  {
            RF = 100
            REMARK: "The transverse layout is uniform"
  }
  IF(rating >0 AND rating <=20)
  {
          RF=10
          REMARK: "There is a very high degree of \
          non-uniformity in the transverse layout"
  }
  IF(rating >20 AND rating <=40)
  {
          RF=30
          REMARK: "There is a high degree of \
          non-uniformity in the transverse layout"
  }
  IF(rating >40 AND rating <=60)
  {
          RF=50
          REMARK: "There is moderate degree of uniformity \
          in the transverse layout"
  }
  IF(rating >60 AND rating <=80)
  {
          RF=70
          REMARK: "There is a high degree of uniformity in \
          the transverse layout"
  }
  IF(rating >80 AND rating <100)
  {
          RF=90
          REMARK: "There is a very high degree of \
          uniformity in the transverse layout"
  }
}
SYSTEM bldg_system
{
  /* Item No. 3 */
  beam to_beam_compatibility: WF = 0.9
  [rating=DetermineBmtoBmCompatibilityNumber()]
  IF(rating == 0)
  {
          RF = 0
          REMARK: "The beam to beam compatibility is bad"
  }
  IF(rating == 100)
  }
          RF = 100
          REMARK: "The beam to beam compatibility is \
          perfect"
  }
  IF(rating >0 AND rating <=20)
  {
          RF=10
          REMARK: "The beam to beam compatibility is bad"
  }
  IF(rating >20 AND rating <=40)
  {
          RF=30
          REMARK: "The beam to beam compatibility is \
          not satisfactory"
  }
  IF(rating >40 AND rating <=60)
  {
```

```
                RF=50
                REMARK: "The beam to beam compatibility is \
                moderate"
        }
        IF(rating >60 AND rating <=80)
        {
                RF=70
                REMARK: "The beam to beam compatibility is high"
        }
        IF(rating >80 AND rating <100)
        {
                RF=90
                REMARK: "The beam to beam compatibility is \
                very high"
        }
    }
    SYSTEM bldg_system
    {
        /* Item No. 4 */
        beam_to_column_compatibility_longitudinal: WF = 0.9
        [rating=DetermineBmtoCmLngCompatibilityNumber()]
        IF(rating == 0)
        {
                RF = 0
                REMARK: "The beam to column compatibility \
                in longitudinal direction is very bad"
        }
        IF(rating == 100)
        {
                RF = 100
                REMARK: "The beam to column compatibility \
                in longitudinal direction is perfect"
        }
        IF(rating >0 AND rating <=20)
        {
                RF=10
                REMARK: "The beam to column compatibility \
                in longitudinal direction is bad"
        }
        IF(rating >20 AND rating <=40)
        {
                RF=30
                REMARK: "The beam to column compatibility \
                in longitudinal direction is not satisfactory"
        }
        IF(rating >40 AND rating <=60)
        {
                RF=50
                REMARK: "The beam to column compatibility \
                in longitudinal direction is moderate"
        }
        IF(rating >60 AND rating <=80)
        {
                RF=70
                REMARK: "The beam to column compatibility \
                in longitudinal direction is high"
        }
        IF(rating >80 AND rating <100)
        {
                RF=90
                REMARK: "The beam to column compatibility \
                in longitudinal direction is very high"
        }
      }
      SYSTEM bldg_system
      {
        /* Item No. 5 */
        beam_to_column_compatibility_transverse: WF = 0.9
        [rating=DetermineBmtoCmTrnCompatibilityNumber()]
        IF(rating == 0)
        {
                RF = 0
                REMARK: "The beam to column compatibility \
                in transverse direction is very bad"
        }
        IF(rating == 100)
        {
                RF = 100
                REMARK: "The beam to column compatibility \
                in transverse direction is perfect"
        }
        IF(rating >0 AND rating <=20)
        {
                RF=10
                REMARK: "The beam to column compatibility \
                in transverse direction is bad"
        }
        IF(rating >20 AND rating <=40)
        {
                RF=30
                REMARK: "The beam to column compatibility \
                in transverse direction is not satisfactory"
        }
        IF(rating >40 AND rating <=60)
        {
                RF=50
                REMARK: "The beam to column compatibility \
                in transverse direction is moderate"
        }
        IF(rating >60 AND rating <=80)
        {
                RF=70
                REMARK: "The beam to column compatibility \
                in transverse direction is high"
        }
        IF(rating >80 AND rating <100)
        {
                RF=90
                REMARK: "The beam to column compatibility \
                in transverse direction is very high"
        }
      }
      SYSTEM bldg_system
      {
        /* Item No. 6 */
        piping_interference_in_same_direction: WF = 0.9
        [rating=DetermineInterferenceInSameDirection()]
        IF(rating == 0)
        {
                RF = 0
                REMARK: "The interference between beam and \
                pipe in the same direction is very bad"
```

```
          }
          IF(rating == 100)
          {
                  RF = 100
                  REMARK: "No interference between beam and pipe \
                  in the same direction"
          }
          IF(rating >0 AND rating <=20)
          {
                  RF=10
                  REMARK: "The interference between beam and \
                  pipe in the same direction is bad"
          }
          IF(rating >20 AND rating <=40)
          {
                  RF=30
                  REMARK: "The interference between beam and \
                  pipe in the same direction is not satisfactory"
          }
          IF(rating >40 AND rating <=60)
          {
                  RF=50
                  REMARK: "The interference between beam and \
                  pipe in the same direction is moderate"
          }
          IF(rating >60 AND rating <=80)
          {
                  RF=70
                  REMARK: "The interference between beam and \
                  pipe in the same direction is high"
          }
          IF(rating >80 AND rating <100)
          {
                  RF=90
                  REMARK: "The interference between beam and \
                  pipe in the same direction is very high"
          }
        }
        SYSTEM bldg_system
        {
          /* Item No. 7 */
          piping_interference_in_across_direction: WF = 0.9
          [rating=DetermineInterferenceInAcrossDirection()]
          IF(rating == 0)
          {
                  RF = 0
                  REMARK: "The interference between beam and \
                  pipe in the across direction is very bad"
          }
          IF(rating == 100)
          {
                  RF = 100
                  REMARK: "No interference between beam and pipe \
                  in the across direction"
          }
          IF(rating >0 AND rating <=20)
          {
                  RF=10
                  REMARK: "The interference between beam and \
                  pipe in the across direction is bad"
          }
```

```
    IF(rating >20 AND rating <=40)
    {
            RF=30
            REMARK: "The interference between beam and \
            pipe in the across direction is not satisfactory"
    }
    IF(rating >40 AND rating <=60)
    {
            RF=50
            REMARK: "The interference between beam and \
            pipe in the across direction is moderate"
    }
    IF(rating >60 AND rating <=80)
    {
            RF=70
            REMARK: "The interference between beam and \
            pipe in the across direction is high"
    }
    IF(rating >80 AND rating <100)
    {
            RF=90
            REMARK: "The interference between beam and \
            pipe in the across direction is very high"
    }
  }
  END
```

Procedures

The synthesised solutions are available in frame bases. The GENCRIT processor uses FMS to retrieve information from the frame bases. If the data stored in frames are required for any computations within the procedures, FMS functions are first called to download these values from the frames into variables. These variables are then used for further computation within the procedure.

The listing of all the *procedures* that are linked to GENCRIT is given below, followed by a brief description of the intent of each *procedure*.

```
int determine_no_of_spacings()
{
 int no_bays,n_spacings=0,i,j;
 double *spacing,rating;
 void *val;
 char frame[10];
 val   = (void *)malloc(100*sizeof(char));
 fms_get_val("lng_layout","no_bays",1,val);
 no_bays = *(int *)val;
 spacing = (double *)malloc(no_bays*sizeof(double));
 for (i=0; i<no_bays; i++)
 {
  sprintf(frame,"bay[%d]",i+1);
  fms_get_val(frame, "spacing", 1,val);
  spacing[i] = *(double *)val;
 }
 for(i=0;i<no_bays;i++)
 {
  int already_exist = 0;
  for (j=0; j<i; j++)
  {
   if(spacing[i] == spacing[j])
   {
       already_exist = 1;
```

```
        break;
        }
    }
    if(!already_exist)
    n_spacings++;
   }
   rating=(double)(no_bays_n_spacings)/(no_bays-1)*100;
   3GENCRIT_proc_value.Dou=rating;
   return(DOU);
}
```

[3] the computed value of rating (a double value) is returned to the critiquing knowledge

The procedure calculates the number of different bay spacings in a particular direction within the layout and returns the number of “different” bays as a percentage of the total number of bays in that direction.

```
int determine_beam_to_beam_compatibility_number()
{
 int no_beams,no,ns_jns=0,comp_no=0,i,j,found=0,ch_no;
 double rating, *depth;
 void *val;
 char frame[10],orientation[5],f_orient[5];
 val = (void *)malloc(100*sizeof(char));
 fms_get_val("bldg_system","no_beams",1,val);
 no_beams = *(int *)val;
 depth = (double *)malloc(no_beams*sizeof(double));
 for (i=0; i<no_beams; i++)
 {
  sprintf(frame,"beam[%d]",i+1);
  fms_get_val(frame, "depth",1,val);
  depth[i] = *(double *)val;
  fms_get_val(frame,"orientation",1,val);
  strcpy (orientation,(char *)val);
  if (i == 0)
  strcpy(f_orient,val);
  if (!found &38;&38; strcmp(f_orient,orientation)!=0)
  {
        found=1;
        ch_no=i;
  }
}
for(i=0;i<ch_no;i++)
{
  for (j=ch_no; j<no_beams; j++)
  {
        no_jns++;
        if(depth[i] != depth[j])
        comp_no++;
  }
 }
 rating=(double)(no_jns-comp_no)/(no_jns)*100;
 GENCRIT_proc-value.Dou=rating;
 return(DOU);
}
```

This procedure calculates the percentage of total joints in the building in which the beams framing in have compatible depths and returns this number

```
int determine_beam_to_column_lng_compatibility_number()
```

```
{
 void *val;
 int i, no_columns, comp_no=0;
 char frame[25], frame1[25];
 double width, dim_trn, rating;
 val   = (void *)malloc(100*sizeof(char));
 fms_get_val("bldg_system","no_colunms",1,val);
 no_columns = *(int *)val;
 for (i=0; i<no_columns; i++)
 {
   sprintf(frame,"column[%d]",i+1);
   fms_get_val(frame,"adj_lng_beam",1,val);
   strcpy (frame1,(char *)val);
   fms_get_val(frame1,"width",1,val);
   width = *(double *)val;
   fms_get_val(frame,"dim_trn",1,val);
   dim_trn = *(double *)val;
   if (width != dim_trn)
   comp_no++;
 }
 rating=(double)(no_columns-comp_no)/(no_columns)*100;
 GENCRIT_proc_value.Dou=rating;
 return(DOU);
}
```

A longitudinal beam and a column that supports it are said to be compatible if the width of the beam is equal to the transverse cross-sectional dimension of that column. The procedure calculates the percentage of the total joints in the building in which such a compatibility exists and returns this number.

```
int determine_beam_to_column_trn_compatibility_number()
{
 void *val;
 int i, no_columns, comp_no=0;
 char frame[25], frame1[25];
 double dim_lng, width, rating;
 val   =(void *)malloc(100*sizeof(char));
 fms_get_val("bldg_system","no_columns",1,val);
 no_columns = \*(int *)val;
 for (i=0; i<no_columns; i++)
 {
  sprintf(frame,"column[%d]",i+1);
  fms_get_val(frame,"adj_trn_beam",1,val);
  strcpy (frame1,(char *)val);
  fms_get_val(frame 1, "width",1,val);
  width = *(double *)val ;
  fms_get_val(frame,"dim_lng",1,val);
  dim_lng = *(double *)val;
  if (width != dim_lng)
  comp_no++;
 }
 rating=(double)(no_columns-comp_no)/(no_columns)* 100;
 GENCRIT_proc_value.Dou=rating;
 return(DOU);
}
```

This function similarly returns the percentage of total joints in the building in which compatibility between transverse beams and columns exists.

```
int detemiine_interference_in_same_direction()
{
 void *val;
 int i, j, no_pipes, no_beams, intr_no=0;
 char drn_p[10], drn_b[10], frame[10], frame1[10];
 double dia, \pos_b, pos_p, pos_b1, pos_b2, flr_height;
 double width, depth, height, rating, z_coord, saf_height;
 val   = (void *)malloc(100*sizeof(char));
 fms_get_val("bldg_system","no_pipes",1,val);
 no_pipes = *(int *)val;
 fms_get_val("bldg_system","flr_height",1,val);
 flr_height = *(double *)val;
 fms_get_val("bldg_system","no_beams",1,val);
 no_beams = *(int *)val;
 for (i=0; i<no_pipes; i++)
 {
  sprintf(frame,"pipe[%d]",i+1);
  fms_get_val(frame,"z_coord",1,val);
  z_coord = *(double *)val;
  fms_get_val(frame, "position",1,val);
  pos_p = *(double *)val;
  fms_get_val(frame,"dia",1,val);
  dia = *(double *)val;
  height = z_coord+dia/2;
  fms_get_val(frame, "orientation",1,val);
  strcpy (drn_p,(char *)val);
  for (j=0; j<no_beams; j++)
  {
        sprintf(frame1,"beam[%d]",j+1);
        fms_get_val(frame1,"orientation",1,val);
        strcpy (drn_b,(char *)val);
        if (strcmp(dm_p,drn_b)==0)
        {
            fms_get_val(frame1,"position",1,val);
            pos_b = *(double *)val;
            fms_get_val(frame1,"width",1,val);
            width = *(double *)val;
            fms_get_val(frame1,"depth",1,val);
            depth = *(double *)val;
            saf_height = flr_height - depth;
            pos_b1 = pos_b+width/2+dia;
            pos_b2 = pos_b-width/2-dia;
            if(pos_b2<=pos_p &38;&38; pos_p<=pos_b1 &38;&38; \
                             height>saf_height) intr_no++;
        }
   }
 }
 rating=(double)(no_pipes-intr_no)/(no_pipes)* 100;
 GENCRIT_proc_value.Dou=rating;
 return(DOU);
}
```

A pipe is said to interfere with a beam running along the same direction if they lie in the same vertical plane and if their z-coordinates overlap. This procedure returns the percentage of the total pipes that interfere with beams running along their direction.

```
int determine_interference_in_across_direction()
{
 void *val;
 int i, j, no_pipes, no_beams, intr_no=0, no_jns=0;
 char drn_p[10], drn_b[10], frame[10], frame1[10];
 double dia, pos_b, pos_p, flr_height;
 double width, depth, height, rating, z_coord, saf_height;
 val = (void *)malloc(100*sizeof(char));
```

```
        fms_get_val("bldg_system","no_pipes",1,val);
        no_pipes = *(int *)val;
        fms_get_val("bldg_system","flr_height",1,val);
        flr_height = *(double *)val;
        fms_get_val("bldg_system","no_beams",1,val);
        no_beams = *(int *)val;
        for (i=0; i<no_pipes; i++)
        {
         sprintf(frame,"pipe[%d]",i+1);
         fms_get_val(frame,"z_coord",1,val);
         z_coord = *(double *)val;
         fms_get_val(frame, "position",1,val);
         pos_p = *(double *)val;
         fms_get_val(frame,"dia",1,val);
         dia = *(double *)val;
         height = z_coord+dia/2;
         fms_get_val(frame,"orientation",1,val);
         strcpy (drn_p,(char *)val);
         for (j=0; j<no_beams; j++)
         {
               sprintf(frame1,"beam[%d]",j+1,val);
               fms_get_val(frame1,"orientation",1,val);
               strcpy (drn_b,(char *)val);
               if (strcmp(drn_p,drn_b)!=0)
               {
                   fms_get_val(frame1,"width",1,val);
                   width = *(double *)val;
                   fms_get_val(frame1,"depth",1,val);
                   depth = *(double *)val;
                   saf_height = flr_height - depth;
                   if height > saf_height intr_no++;
                   no_jns++;
               }
         }
       }
       rating=(double)(no_jns_intr_no)/(no_jns)*100;
       GENCRIT_proc_value.Dou=rating;
       return(DOU);
       }
```

This procedure similarly returns the percentage of pipes that interfere with beams that run across them.

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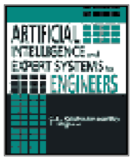

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